8-2016

Manipulating air and root-zone temperature for energy-efficient floriculture crop production

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Graduate School Form
30 Updated 12/26/2015

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By Madeline W. Olberg

Entitled

Manipulating air and root-zone temperature for energy-efficient floriculture crop production

For the degree of Master of Science

Is approved by the final examining committee:

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MANIPULATING AIR AND ROOT-ZONE TEMPERATURE FOR ENERGY-EFFICIENT FLORICULTURE CROP PRODUCTION

A Thesis

Submitted to the Faculty

of

Purdue University

by

Madeline W. Olberg

In Partial Fulfillment of the

Requirements for the Degree

of

Master of Science

August 2016

Purdue University

West Lafayette, Indiana

I dedicate this thesis to my brilliant and compassionate parents, Andrea Worthington and Rob Olberg. I could not have done it without their infinite support via speaker phone.

ACKNOWLEDGEMENTS

I would like to wholeheartedly thank everyone that has touched my life over the past two years. You each contributed greatly to make this achievement attainable.

To my major advisor, Dr. Roberto Lopez, thank you for giving me this opportunity and for supporting me through all the ups and downs of research and writing. I am honored to have been here through the exciting beginnings of your beautiful family. And to my committee members, Dr. Cary Mitchell and Dr. Neil Mattson, thank you for your advice, revisions, and flexibility. I have truly appreciated your guidance and encouragement every step of the way.

To my irreplaceable lab-mates, Garrett Owen and Josh Craver, thank you for your love, laughter, and kindness day-in and day-out. You were the best comrades, dancing partners, back-up singers, therapists, consultants, editors, and big brothers I could ever have asked for. And to my incredible Indiana companions, Jacob Franzen, Zach Oravec, Shelby Craver, and Libby Shepard, thank you for your undying friendship and reassurance. You all were there for my many highs and lows to keep me smiling.

To my family, Andrea Worthington, Rob Olberg, and Logan Olberg, thank you for igniting my passion for learning early on in life and for your endless support and love since. And to my furry aficionados, Ella, Hallie, and Tucker, thank you for keeping life amusing and for giving me an excuse to get out of the office every night.

To the wonderful greenhouse and high tunnel teams, Rob Eddy, Michael Russell, Dan Hahn, and Nathan Linder, thank you for your continuous support and assistance in the greenhouse, high tunnel, and beyond. And to our trusty undergraduate workforce, Andrea Hilligoss, Alyssa Myers, Maria Del Rosario Del Rio, Kristine Binkley, Kyra Brown, Brenton Strim, Jun Hayashi, Hilary Burkhardt, and Jill Malecki, thank you for your friendship and hours of entertainment and assistance. And finally, to all the other graduate students, faculty, and staff in the Department of Horticulture and Landscape Architecture, a sincere thank you for making this all possible.

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LIST OF ABBREVIATIONS

Abbreviation	Description
BAI	bract area index
BAHR	bract area-to-height ratio
DIF	day and night temperature differentials
DLI	daily light integral
GI	growth index
HAF	horizontal airflow
HPS	high-pressure sodium
HT	high tunnel
LSD	least significant difference
MDT	mean daily temperature
PGR	plant-growth regulator
PAR	photosynthetically active radiation
PPF	photosynthetic photon flux
RDM	root dry mass
RTF	reduced temperature finishing
RZH	root-zone heating
SDM	shoot dry mass
T_b	base temperature
T_{max}	maximum temperature
T_{opt}	optimum temperature
TTA	time to anthesis
TTF	time to flower
TTM	time to marketability
Q_{10}	temperature coefficient of a reaction
ΔGI	change in growth index
ΔHt	change in height

ABSTRACT

Olberg, Madeline W. M.S., Purdue University, August 2016. Manipulating Air and Root-zone Temperature for Energy-efficient Floriculture Crop Production. Major Professor: Roberto G. Lopez.

Given the high energy costs for greenhouse floriculture production, growers are constantly searching for more energy-efficient methods of production. For example, some growers will lower greenhouse air temperature set points or grow crops in unheated high tunnels (HTs) or outdoors in order to minimize or eliminate heating costs. Unfortunately, development can be delayed and morphology can be altered if the mean daily air temperature (MDT) is reduced. We proposed that reducing MDT in combination with root-zone heating (RZH) could be an energy-efficient method for producing high-quality floriculture crops without significant delays. Unheated HT and unprotected outdoor production are very low-cost systems for bedding plant production, but little information is available on crop developmental and morphological effects. The objectives of this study were, therefore, to quantify growth and development of 1) red poinsettia cultivars finished under reduced MDT in combination with RZH (Experiment 1); 2) several petunia cultivars and recombinant inbred lines grown under reduced MDT in combination with RZH (Experiment 2); and 3) cold-tolerant and cold-intermediate annual bedding plants grown in an unheated HT or unprotected outdoor growing area with or without an acclimation period (Experiment 3). In Experiments 1 and 2, time to flower

decreased with increasing root-zone temperature across species and cultivars. Overall, high-quality poinsettias can be produced without delay if MDT is reduced by 5 °C, but a RZH set point of ≥24 °C is employed during the finish stage. Similarly, MDT can be reduced to 15 °C for petunia production when a RZH set point of 27 °C is utilized. In Experiment 3, flowering of all species was delayed when plants were grown outdoors compared to in the HT. However, high-quality annual bedding plants could be produced outdoors, depending on species, given the increased daily light integral (DLI) and air movement to keep plants compact. When plants were given a one-week acclimation period in the HT prior to outdoor production, almost all species were delayed less than 1 week compared to those grown in the HT only. When producing crops outdoors, growers must be aware of the risk of delay or crop loss due to extreme weather. Generally, high-quality floriculture crops can be produced with minimized cost for heating in a greenhouse with reduced MDT in combination with RZH, as well as in an unheated HT or outdoors, depending on species and weather conditions.

LITERATURE REVIEW

Temperature

Temperature has a major influence on various physiological processes of plant function and growth, but most notably it influences the rate of plant development (Blanchard and Runkle, 2011; Hicklenton and Heins, 1997). Temperature is defined as a measure of the thermal energy of matter, meaning the relative amount of vibration or movement of molecules and atoms (Hicklenton and Heins, 1997; Janick, 1986). Plant temperature is therefore based on the balance of thermal energy transfer between plants and their environment. These energy-exchange processes include conduction, convection, absorption of radiation, re-radiation, and evaporative cooling via transpiration (Fitter and Hay, 1987; Hicklenton and Heins, 1997). Energy equilibrium can be represented as:

$$E_s=E_i+E_r+E_c+E_l+E_m \quad [1]$$

Where E_s is the instantaneous sum of the energy-exchange processes, creating the dynamic shifts in plant temperature; E_i is the total radiation absorbed; E_r is the re-radiated long-wavelength radiation; E_c represents the energy transferred by conduction and convection; E_l represents the latent heat transfer, determined by evaporation or condensation at leaf level; and E_m is the net heat produced or consumed in metabolic processes (Hicklenton and Heins, 1997). When E_s equals zero, the net energy in and out of the plant is balanced and therefore there is no change in plant temperature. This

scenario is rare as each component is continually shifting in both a controlled environment and field setting (Hicklenton and Heins, 1997; Raschke, 1960). The energy related to metabolism tends to be insignificant compared to other heat-transfer processes, and is generally ignored when examining heat exchange (Fitter and Hay, 1987; Hicklenton and Heins, 1997). All other factors contribute largely to plant temperature, and given this complex system of energy transfer, temperature is also influenced by other environmental factors, such as humidity and light intensity (Blanchard and Runkle, 2011). In total, this makes for a very complicated balance for controlling and maintaining optimal temperatures, so each aspect of the dynamic equilibrium must be well understood.

Radiation refers to the transfer of energy as electromagnetic waves (Janick, 1986). Absorption of photosynthetically active radiation (PAR), from 400 to 700 nm, is of great importance to a plant for the light reactions of photosynthesis. Excess absorbed radiation, which is not used in the light reactions, transforms into thermal energy, raising plant temperature, or is given off as fluorescence (Fitter and Hay, 1987; Janick, 1986; Leopold, 1964). In fact, less than 5% of net radiation is used for photosynthetic and metabolic activities, tending to be small enough to ignore (Hanan, 1998; Hicklenton and Heins, 1997). While most of the absorbed radiation is within the range of 400 to 700 nm, some infrared radiation is absorbed (700 to 1500 nm), though most is transmitted through or reflected by leaves; but a considerable exchange of far-infrared radiation (1500 to 30,000 nm) contributes highly to the thermal energy of a plant (Leopold, 1964; Mellor et al., 1964). Of the radiation absorbed by a plant, up to 75% is re-radiated as far-infrared, long-wave radiation, accounting for the majority of heat dissipation when total incoming and

outgoing radiation are considered (Hicklenton and Heins, 1997; Mellor et al., 1964). Given this high potential of heat loss by re-radiation, especially at night, retractable thermal energy curtains are often employed by greenhouse growers for heat retention (Blanchard and Runkle, 2011). Thermal screens also reflect radiated heat back to the plants, and prevent thermal energy from escaping the greenhouse (Nelson, 2003). Other mechanisms by which plants dissipate much of their thermal energy include conduction, convection, and transpiration, occurring primarily at the leaf surface (Hicklenton and Heins, 1997).

Conduction is the movement of thermal energy at the molecular level along a temperature gradient (Hicklenton and Heins, 1997). Heat transfer in the soil or media to the roots is primarily through conduction (Janick, 1986). Conduction between leaf cells and air molecules can be minimal due to the low conductivity of air, but is increased with air flow, and hence is closely connected to convection (Hicklenton and Heins, 1997; Janick, 1986). Generally, heat exchange is between the leaf and boundary layer, 1 to 2 mm of still air at the leaf surface, but with increasing air movement this heat exchange increases linearly (Leopold, 1964).

Convection describes heat exchange by the movement of air based on temperature gradients causing changes in air density and pressure (Hicklenton and Heins, 1997; Janick, 1986). Naturally, as air in the boundary layer gains thermal energy from the leaf via conduction, the air expands, decreasing its density, therefore causing it to rise and be replaced by cooler, denser air (Hicklenton and Heins, 1997). With increased air movement, such convective transfer of thermal energy can be increased. To ensure continual air circulation, convection tubes or horizontal airflow (HAF) systems are

commonly used; this increases convection at the leaf surface, as well as temperature uniformity throughout the greenhouse (Nelson, 2003).

The final and most plant-regulated heat exchange is due to the latent heat of evaporation from the leaves through transpiration (Hicklenton and Heins, 1997; Leopold, 1964). The potential transpiration rate relates directly to the vapor pressure gradient between the plant and air (Hicklenton and Heins, 1997; Mellor et al., 1964). The evaporation of water from the leaf through stomata requires a relatively large amount of thermal energy. In fact, 2.436 J are required to evaporate 1 g of water, at 25 °C, which thereby reduces leaf temperature as the thermal energy is used (Hicklenton and Heins, 1997). One third of dissipated thermal energy is lost via transpiration, highlighting the great importance of this process for regulating plant temperature (Leopold, 1964). Leaf temperature can be lower than air temperature when transpiration rate is high. This is often caused by a large vapor pressure gradient due to high temperature and low humidity (Hicklenton and Heins, 1997).

Plant temperature, resulting from the equilibrium of radiation, conduction, convection, and transpiration, determines the potential for metabolic reactions, as well as plant growth and developmental responses. Temperature has a great effect on both physical and chemical processes, and therefore translates to having a great effect on biological responses at different temperatures (Janick, 1986). Reaction rates, enzyme activity, diffusion rates, and solubility are all related to temperature (Janick, 1986; Leopold, 1964). The temperature coefficient of a reaction, or Q_{10}, is the quantitative measure of increase in reaction rate with increased temperature, where:

$$Q_{10} = \frac{\text{Rate at temperature (T + 10 °C)}}{\text{Rate at temperature T}} \qquad [2]$$

(Fitter and Hay, 1987). The Q_{10} of most reactions *in vitro* is around two, meaning that the reaction rate doubles with each increase of 10 °C (Fitter and Hay, 1987). This increase is due to increased molecular energy at higher temperatures as well as the increase in molecular movement. In physical processes, such as diffusion, the increased molecular movement associated with higher temperatures causes reactants to come into contact more frequently, hence increasing the rate of reaction (Leopold, 1964). For enzymatic reactions, the higher molecular energy allows enzymes to reach their activation threshold more quickly and more often, thus increasing the rate of reactions (Leopold, 1964). At even higher temperatures, reactions rates often decrease, if not totally cease, as thermal denaturation of the reactants or enzymes occurs (Fitter and Hay, 1987).

The solubility of oxygen (O_2) and carbon dioxide (CO_2) are also altered depending on temperature. These are two of the most influential molecules in basic plant metabolism, which can have a great effect on biochemical processes within a plant (Leopold, 1964). At lower temperatures, O_2 and CO_2 are more soluble. Therefore, there is a greater concentration of these molecules in the plant sap (Janick, 1986; Leopold, 1964). This alteration can affect both chemical and physical properties of the sap, and hence can greatly affect many of the biochemical processes occurring (Leopold, 1964).

The various adjustments associated with temperature change affect various plant processes differently. For example, photosynthesis occurs from 0 to 40 °C with the highest rates occurring from 20 to 30 °C. Meanwhile, respiration rates are low around 20 °C, but increase rapidly as temperatures increase (Fitter and Hay, 1987). At a certain

point, gross photosynthesis and respiration are equal, thus net photosynthesis is zero. Net photosynthesis is what drives growth. Therefore, the interaction of the effect of temperature on photosynthesis as well as respiration must be considered for determination of the effect of temperature on growth (Fitter and Hay, 1987; Janick, 1986). Other physical properties are also affected by temperature, such as the viscosity of water and membrane permeability, which further contribute to alteration of potential growth (Janick, 1986). Along with effects on growth, each process associated with development is also influenced by temperature independently, including flowering, fruit and seed set, dormancy, and maturation (Janick, 1986).

The 24-h air temperature average, or mean daily temperature (MDT), predominantly influences the rate of plant development (Blanchard and Runkle, 2011a; Blanchard and Runkle, 2011b; Blanchard et al., 2011; Nelson, 2003; Vaid and Runkle, 2013). Plant development can be described as the process of organ differentiation and maturation and measured as the time to visible bud, time to flowering (TTF), or other developmental parameters. Generally, plants have a base temperature (T_b), an optimum temperature (T_{opt}) and a maximum temperature (T_{max}), as shown in Figure 1.1. Rate of plant development is zero at or below the species- and cultivar-specific T_b, increases linearly between T_b and T_{opt}, is most rapid at T_{opt}, and ceases at and above T_{max} (Adams et al., 1998; Blanchard and Runkle, 2011b; Dole and Wilkins, 1999).

When plants are grown under a range of MDTs, these parameters, relevant to rate of plant development to flowering (i.e. 1/days to flower), can be estimated by regression analysis, using:

$$\frac{1}{days\ to\ flower} = A \times (MDT - T_b) \times (T_{max} - MDT)^B \qquad [3]$$

where $$A = \frac{R_{max}}{[(T_{opt}-T_b)\times(T_{max}-T_{opt})^{B}]}$$ [4]

and $$B = \frac{(T_{max}-T_{opt})}{(T_{opt}-T_b)}$$ [5]

(Blanchard and Runkle, 2011b). In above, R_{max} is the maximum rate of development to flowering. Given this model and the definition of T_b and T_{max}, if MDT is $\leq T_b$ or $\geq T_{max}$, then developmental rate equals zero; and when MDT = T_{opt}, plants develop at the R_{max}. The 'B' value defines the asymmetrical skew of the model, such that developmental rate increases at a lesser slope when T_b<MDT$\leq T_{opt}$ and decreases at a greater slope when T_{opt}<MDT<T_{max}. In some cases, an exponential function fits the model better, in which case the model is as follows:

$$\frac{1}{days\ to\ flower} = R_{max} \times \{1 - \exp[-C \times (MDT - T_b)]\}$$ [6]

(Blanchard and Runkle, 2011b). In this model, 'C' defines the skew of the function.

Plants can be categorized based on their T_b as cold-tolerant, cold-intermediate, or cold-sensitive, when $T_b \leq 4$, $4 < T_b < 7$, or $T_b \geq 7$, respectively (Blanchard and Runkle, 2011b). For example, snapdragon (*Antirrhinum majus* 'Montego Orange Bicolor') is categorized as a cold-tolerant plant with a T_b, T_{opt}, and T_{max} of 2.0, 25.7, and 30.3 °C; dahlia (*Dahlia ×hybrida* 'Figaro Mix') is categorized as cold-intermediate with a T_b, T_{opt}, and T_{max} of 5.6, 19.1, and 30.4 °C; and blue salvia (*Salvia farinacea* 'Victoria Blue') is categorized as cold-sensitive with a T_b, T_{opt}, and T_{max} of 9.4, 28.0, and 31.0 °C, respectively (Blanchard and Runkle, 2011b). Growers generally target a MDT within the linear range, between T_b and T_{opt}, and adjust day and night temperatures to alter and optimize growth and development (Blanchard and Runkle, 2011b; Lopez and Runkle, 2014; Vaid et al., 2014). Although at a MDT at or near T_{opt} plant development is most

rapid, a reduction in quality can occur, such as longer, thinner stems and smaller flowers (Dole and Wilkins, 1999; Nelson, 2003).

The difference between day and night temperature (DIF = DT − NT) can also affect the growth and developmental rate of crops. Numerous studies have focused on using DIF to control height, flowering, and other characteristics of many species, including various bedding and potted crops (Berghage and Heins; 1991; Erwin et al., 1989; Merritt and Ting, 1995; Myster and Moe, 1995). Stem elongation has been found to increase with increasing DIF from −15 to 15 °C for lily (*Lilium longiflorum* ‘Nellie White’) (Erwin et al., 1989). This trend has also been observed with various other species, such as poinsettia (*Euphorbia pulcherrima*), cucumber (*Cucumis sativus*), and tall verbena (*Verbena bonariensis*) (Berghage and Heins, 1991; Moe et al., 1992; Shimizu and Heins, 2000; Xiong et al., 2002). Day and night temperature differentials have also been found to affect leaf and shoot orientation, leaf chlorophyll content, and flowering (Myster and Moe, 1995).

Overall, temperature is of great importance to the growth, development, and morphology of all plants. Mean temperatures, temperature fluctuations, and temperature extremes all can cause major and differing effects, and therefore research in these areas continues to be important. To optimize plant growth, maturation, and even yield, a full understanding of how variations in temperature affect different species is necessary; as growers continually strive to control and alter environmental conditions, including temperature, in order to control growth, development, and morphology of their crops.

Greenhouse Heating

Greenhouse heating is an essential aspect of specialty-crop production, especially at northern latitudes. Heating is one of the highest costs of production, second only to labor, and can account for 10 to 30% of total operating costs for a greenhouse (Brumfield, 2007; Lopez, 2008). Greenhouse heating consumes 65 to 85% of the total energy budget, though this depends on the amount of heat required, equipment expenses, fuel price and availability, and size, style, and age of the greenhouse structure (Dole and Wilkins, 1999; Runkle and Both, 2011; Sanford, 2011). Typical greenhouse heating methods include forced-air unit heaters, central heating with boilers, or infrared-radiant heating (Nelson, 2003).

Unit heaters are commonly used given their low capital and installation costs, reliability, and ease of installation and use (Hanan, 1998; Sanford, 2011). The cost of this system, including installation, is generally $11 to $16 (USD) per square meter of greenhouse floor (Nelson, 2012). This heating method uses forced air, which is heated as it passes by thin-walled metal tubes filled with hot exhaust from the combustion of natural gas, oil, kerosene, or liquid propane (Dole and Wilkins, 1999). Natural gas and propane are the most commonly used fuels. These heaters are generally located above plant level, and HAF fans or convection tubes are used to distribute the warm air throughout the greenhouse (Dole and Wilkins, 1999; Nelson, 2003).

Central-heated greenhouses typically use hot water or steam that is heated in one or more central boilers, and then is pumped out to the houses through pipe coils to exchange heat with air in the greenhouse (Dole and Wilkins, 1999). Installation of this system generally costs $48 to $65 (USD) per square meter of greenhouse floor, including

all pipe coil and installation, depending on number and size of greenhouse zones and amount of heating required (Nelson, 2012). One cost-reducing advantage of this system is that it can easily incorporate a boiler that can use alternative fuel sources such as coal, heavy oils, or biomass, such as wood chips, logs, switch grass, corn, or bark (Hanan, 1998; Nelson, 2012). This system also can provide improved uniformity of heat distribution and heat at plant level.

Infrared-radiant heating systems have been reported to save 30 to 50% on fuel costs, compared to unit heating systems (Hanan, 1998; Nelson, 2012). Installation costs for this system range from $27 to $48 (USD) per square meter of greenhouse floor, depending on the location and latitude of the greenhouse (Nelson, 2012). This system burns fuel (propane or natural gas) mixed with air in a pipe to extreme temperatures, which then emits infrared radiation (Dole and Wilkins, 1999). Since the pipes can reach temperatures as high as 480 °C, they are placed high above the plant surface and away from human contact (Nelson, 2003). The electromagnetic waves travel through the air, are absorbed by objects or plants, and the energy is converted to heat (Nelson, 2003). Therefore, this system not only heats plant leaves and shoot surfaces, but also heats benches and floors (Dole and Wilkins, 1999). This system does not directly heat the air in the greenhouse, but rather, the air receives heat only indirectly from the benches, floors, and plants. The air temperatures in greenhouses heated with this system are about 3 to 6 °C cooler than a central or unit-heated greenhouse, but can achieve similar plant temperatures (Dole and Wilkins, 1999; Nelson, 2003). While this system uses less energy, heat distribution in the house and canopy is variable and temperatures can fluctuate rapidly, making this system less ideal (Dole and Wilkins, 1999; Hanan, 1998).

An alternative to heating greenhouse air is providing root-zone heating (RZH). Bench-top or in-floor RZH systems can supply heat directly to the root-zone, without directly heating the air in the greenhouse, and thus, create a microclimate at plant level. One common example of RZH is a microclimate tubing system, consisting of a series of black rubber tubes on the bench or in the floor through which hot water (~49 °C) circulates (Dole and Wilkins, 1999; Gerovac, 2014). In bench-top systems, containers or trays can be placed directly onto the rubber tubing, thus heating the tray or container, media, root-zone, and plant by conduction; and heating the plant canopy as heat rises by convection from the bench, creating a warm microclimate above the bench (Dole and Wilkins, 1999; Sachs et al., 1992; Vogelezang, 1988; Vogelezang and van Weel, 1989). These RZH systems are then controlled by a separate thermostat system, which measures media temperature (Hanan, 1998). Growers cannot rely entirely on RZH systems to heat greenhouse air, so generally another supplemental heating system is required to maintain suitable air and plant temperatures within the greenhouse, as well as to prevent pipes from freezing (Christenbury, 1990; Dole and Wilkins, 1999). However, 25 to 75% of heating needs can be met through RZH (Bartok, 2006; Bartok, 2013; Hanan, 1998). Additionally, up to 50% energy savings have been reported using bench-top RZH (Sachs et al., 1992).

Regardless of the heating method used, greenhouse growers in northern climates must be able to provide heat to their crops to ensure growth, development, and quality. This turns out to be a major cost of production and is only becoming more expensive with increasing energy prices, such as for propane and natural gas. To counteract this trend, many growers have begun adopting various practices and technologies to decrease energy

costs for greenhouse heating. Such implementations include installing thermal energy curtains, switching to alternative fuel sources, installing more efficient boilers and unit heaters, adding insulation, and fixing air leaks (Brumfield, 2007; Runkle and Both, 2011). Many growers are also using careful crop scheduling and temperature maintenance to ensure that they supply only what the crop needs to avoid any superfluous heating. This is increasingly necessary given fluctuations in energy costs in recent years. For example, the cost of propane and natural gas increased 72 and 44%, respectively, in the past 15 years (EIA, 2015a; EIA, 2015b). Therefore, growers strive to produce plants with lower energy inputs in order to decrease cost and hence increase profit margins.

Poinsettia Production

Poinsettias continue to be a popular crop during the holiday season and dominate among overall potted-flowering-plant sales, totaling 33.2 million pots sold in 2014 (USDA, 2015). In 2014, the wholesale value totaled $141 million USD and accounted for 18% of total potted-flowering-plant sales (USDA, 2015). However, the wholesale price has risen only 12% since 2000, from an average of $4.21 in 2000 to $4.73 in 2014, for pots >12.7 cm (USDA, 2001; USDA, 2015); while natural gas and propane prices have risen 35 and 70%, respectively (EIA, 2015a; EIA, 2015b).

Poinsettias are propagated from vegetative cuttings harvested from stock plants. While some growers produce poinsettia stock plants in North America, the majority are produced in offshore production facilities located in Central America and Africa, where production and labor costs are lower (Ecke III et al., 2004). Vegetative cuttings are excised from the terminal stems of stock plants and are generally 5 to 6 cm in length,

from base to apical meristem (Ecke III et al., 2004). Unrooted cuttings are shipped to the U.S., received by propagators, and rooted in foam, Rockwool, or peat-based substrates (Dole and Wilkins, 1999; Ecke III et al., 2004). However, growers can also purchase rooted cuttings from propagators to plant in late summer. By purchasing rooted or unrooted cuttings, growers not only ensure quality, but also free up valuable production space throughout the spring that would otherwise be filled with stock plants (Ecke III et al., 2004).

Once transplanted, poinsettias require a period of vegetative growth, which varies in length depending on geographic location, cultivar vigor, container size, and desired height and size of the final plant (Ecke III et al., 2004). Once cuttings root (10-14 d), poinsettia plants are pinched, removing the apical meristem to promote branching. Plants then undergo another period of vegetative growth prior to flower initiation (Ecke III et al., 2004). Poinsettias are short-day photoperiodic plants, requiring at least 11.8 hours of darkness for floral induction and then anywhere from 6 to 10 weeks at the critical photoperiod to flower (Dole and Wilkins, 1999). This critical day length has been found to be both temperature and cultivar dependent (Kristoffersen, 1969; Schnelle and Barrett, 2011; Wieland et al., 2000). For example, colored bract number per lateral branch decreased by 4 for poinsettia ‘Early Red Splendor’ when night length was decreased from 13.5 to 12.5 h, but only by 0.8 for poinsettia ‘Prestige Early Red’ (Schnelle and Barrett, 2011). Critical day length has also been reported to be shorter when day temperature is increased, but longer when night temperature is increased (Kristoffersen, 1969). Generally, under natural day lengths, flower initiation occurs between 20 September and 01 October (Ecke III et al., 2004). Photoperiod manipulation is generally accomplished

using natural day lengths, day-extension (DE) or night-interruption (NI) lighting, or blackout cloth (Wieland et al., 2000). Under a natural day, plants are allowed to develop with normal day length changes with the season progression, whereas DE or NI lighting can create an artificial long day. For poinsettia production, DE or NI photoperiodic lighting is terminated around 01 October and plants then receive a short day from the natural day length (Wieland et al., 2000). To employ blackout cloth, a grower will pull opaque blackout cloth over the benches and plants to prevent any light from reaching the crop for a set length of time every night, generally around 14 to 16 h (Wieland et al., 2000). Wieland et al. (2000) reported that plants developed significantly slower under natural day lengths than when blackout cloth was employed.

Poinsettia floral development is temperature dependent. Base temperature of poinsettia is around 10 °C, below which the plant ceases to develop; therefore classifying poinsettia as a cold-sensitive crop (Berghage et al., 1990). Rate of development for poinsettia increases linearly with increasing temperature from 16 to 22 °C, reaches a maximum rate at the T_{opt}, between 23 and 26 °C, then decreases above that point (Ecke III et al., 2004). For example, time from visible bud to anthesis decreased by 10 d with an increase in air temperature from 18 to 22 °C (Odula, 2011). Delays in development due to high temperature, or heat delay, is also commonly observed in poinsettia crops, if night temperatures exceed 22 °C (Ecke III et al., 2004). For example, flowering of the late season cultivars ‘Prestige Red’ and ‘Success Red’ was delayed by 15 and 18 d, respectively, when exposed to day/night temperatures of 28/24 °C for 28 d compared to 24/21 °C (Schnelle et al., 2006). Similarly, night temperatures of 29 °C completely prevented flowering of poinsettia ‘Annette Hegg Dark Red’ (Berghage and Heins, 1991).

Low air temperatures can also delay development of poinsettias (Camberato et al, 2012; Tsujita and Craig, 1980). For example, Camberato et al. (2012) reported an increase in time to anthesis of 15 to 22 d when day/night air temperatures were decreased from 24/19 °C to 20/13 °C. Low night air temperatures of 13 °C, initiated 4 to 5 weeks after the start of short days, significantly reduced the number of colored bracts for poinsettia 'Annette Hegg Dark Red' compared to night temperatures of 18 °C (Tsujita and Craig, 1980). Tsujita and Craig (1980) also reported a delay in maturity by 6 d for poinsettia 'Annette Hegg Dark Red' when plants were grown with reduced night air temperatures from 17 to 11 °C for just half of the night (7 h) starting at initiation of short days. Odula (2011) reported no visible bud if poinsettia plants were grown at 15.5 °C.

Day and night temperature differentials can also affect developmental rate of poinsettia, but mainly affects plant height and quality. Moe et al. (1992) reported that a negative DIF delayed time to visible cyathia and time to marketability for poinsettia 'Starlight' and 'Lilo', while a zero DIF was reported to cause the earliest flowering and marketability. Height of poinsettia 'Starlight' and 'Lilo' grown under a negative DIF was reduced by about 25% compared to plants grown under a zero or positive DIF (Moe et al., 1992). Negative DIF also resulted in a reduced number of lateral shoots, shorter leaves, and shorter petioles for poinsettia 'Starlight' (Moe et al., 1992). These characteristics could be considered beneficial to a grower, if a reduction in plant size is desirable, for bench-space optimization or shipping requirements.

Poinsettia height is therefore often controlled by temperature manipulation, as well as by use of chemical plant-growth regulators (PGRs). Regarding MDT, stem elongation rate was ≈5 times greater when poinsettia 'Viking' and 'Paul Mikkelsen' were

grown at 24 °C compared to 15 °C (Kristoffersen, 1969). Internode length has also been reported to be a function of DIF (Berghage and Heins, 1991). A positive relationship is observed between DIF and internode length; as an increased DIF causes an increase in internode length, whereas decreased DIF decreases internode length (Berghage and Heins, 1991). To limit the use of PGRs to control poinsettia height, growers often avoid a large positive DIF. Various models and computerized decision support software have been created to manage and control poinsettia height and growth by manipulation of temperature and PGR applications (Berghage and Heins, 1991; Fisher and Heins, 1995; Frantz et al., 2010).

Bract size and number are also of great importance for poinsettia quality. Liu and Heins (2002) focused on photothermal ratio, the ratio of radiant energy to thermal energy (moles of PAR/degree-day) as a cause for differences in bract area and inflorescence diameter. When photothermal ratio increased during the reproductive phase (after short day initiation), bract area and inflorescence diameter of poinsettia ‘Freedom’ increased by 45 and 23%, respectively. Schnelle and Barrett (2011) also reported a reduction in the number of colored bracts of poinsettia ‘Prestige Early Red’, ‘Freedom Red’, and ‘Early Red Splendor’ when grown at 27 °C compared to 21 or 24 °C, under the same DLI. An increased hue angle, corresponding with increased green versus red hues, was also reported for poinsettia ‘Early Red Splendor’ with an increase in temperature from 24 to 27 °C indicating delay and lower crop quality (Schnelle and Barrett, 2011). Bract area of poinsettia ‘Annette Hegg Dark Red’ was significantly reduced when night temperatures were reduced to 13 °C anywhere from 4 to 7 weeks after initiation of short days. Bract diameter was also reduced for plants grown with a split night, 7 h at 17 °C and 7 h at 11

°C, compared to a constant 17 °C night temperature (Tsujita and Craig, 1980). Overall, it can be concluded that excessively high or low temperatures can lead to delays in crop development, as well as decreased poinsettia crop quality.

Greenhouse and High Tunnel Production

Greenhouse production of annual bedding plants at northern latitudes generally occurs from mid-winter to late spring. During this time, greenhouse heating is necessary to sustain plant growth and development. As previously discussed, this renders a large cost to the greenhouse operation and, hence, many growers have begun implementing various measures to reduce these heating costs (Brumfield, 2007). If production heating costs can be reduced, profit margins can increase. Some growers have therefore begun growing annual bedding plant crops at lower greenhouse air temperature set points, in high tunnels (HTs), or even growing outside (Lopez, 2008). Unfortunately, delays in development are caused by reduced air temperatures, especially for cold-sensitive and cold-intermediate species (Lopez and Runkle, 2014). These delays can increase production time, thereby increasing energy costs, and can potentially cause growers to miss market dates.

Reduced air temperatures result in slower development rates. For example, Vaid and Runkle (2013) reported geranium (*Pelargonium* ×*hortorum* ‘Ringo 2000 Deep Red’) and osteospermum (*Osteospermum ecklonis* ‘Asti Purple’) as delayed in flowering by 53 and 34%, respectively, when grown at 17 °C compared to 23 °C. Similarly, as MDT decreased from 20 to 15 °C, African marigold (*Tagetes erecta* ‘Antigua Primrose’), dianthus (*Dianthus chinensis* ‘Super Parfait Raspberry’), cosmos (*Cosmos sulphureus*

‘Cosmic Orange’), verbena (*Verbena ×hybrida* ‘Quartz Waterfall Mix’), and zinnia (*Zinnia elegans* ‘Dreamland Coral’) increased in TTF by 11 to 18 d (Blanchard and Runkle, 2011b). This effect is even greater for cold-sensitive species, such as pentas (*Pentas lanceolata* ‘Fraffiti Lavender’; T_b=9.3 °C), which had an increase in TTF of 32 d with the same 5 °C decrease in MDT (Blanchard and Runkle, 2011b).

Another alternative to reduce heating costs is the use of HTs for crop production. High tunnels are simple structures with one or two layers of polyethylene that provide some protection to the crop, but have no additional heat supply beyond natural solar radiation (Coolong, 2012). High tunnel production has been found to be a sustainable, but risky, means of production for some bedding plants after transplanting from plugs or rooted liners (Currey et al., 2012). Most annual bedding plants grown in HTs, compared to those grown in greenhouses, exhibit a delay in development (Currey et al., 2014). For example, when transplanted on 08 Apr., angelonia (*Angelonia augustifolia* ‘Serena Lavender’) and petunia ‘Dreams Midnight’ took 12 and 8 d longer to flower in an unheated HT than in a heated greenhouse, respectively (Currey et al., 2014). Flowering of snapdragon plants has also been reported to be delayed by 20 to 26 d when grown in an unheated HT compared to a heated greenhouse (Currey et al., 2014; Gerovac et al., 2015). Gerovac et al. (2015) reported that dianthus ‘Telstar Crimson’ and petunia ‘Wave Pink’ took 8 d longer to flower in an unheated HT than in a heated greenhouse when transplanted on week 13, but had no significant difference in TTF if transplanted on week 15. This suggests that delays in TTF can be prevented for some species by later transplant dates, but market dates will therefore be delayed as well.

Some growers also implement outdoor production for additional space and energy savings, especially for late spring and summer crops, but little is published on the effects of outdoor production on annual bedding plants. Though some growers find outdoor production to be viable and useful, this seems to be an even more risky production method than HT production, as plants have little to no protection from the elements (Crum, 2008). Research is therefore needed to examine the benefits and risks of producing various species of annual bedding crops outdoors versus in HTs or greenhouses.

Effects of Root-zone Temperature

Root-zone heating causes a change in overall plant temperature by creating a microenvironment at plant level, raising plant temperature as heat from the bench transfers to the plant and canopy via conduction and convection (Sachs et al., 1992; Vogelezang, 1988; Vogelezang and van Weel, 1989). Altering the temperature of the root-zone therefore alters growth and development, which has been observed in a number of studies to date. Root-zone heating can often allow for decreased heating costs as heat is supplied directly to the plants and their nearby airspace, rather than the entire airspace of the greenhouse (Bartok, 2006). Consequently, using reduced air temperatures in combination with RZH could be a sustainable method for decreasing energy costs for greenhouse heating during production. Research on the effects of this heating regime on plant growth and development is thus necessary prior to commercial implementation.

Root-zone temperature affects plant development, given the direct relation of plant temperature and rate of development. Wulster and Janes (1984) determined that

poinsettia ‘Brilliant Annette Hegg’ plants matured earlier, in terms of both bract size and color and anthesis, when grown with RZH set points of 23 to 32 °C compared to 18 °C. Janes et al. (1981) similarly found that poinsettia ‘V-10’ and ‘Annette Hegg Supreme’ grown with RZH set points of 26 to 38 °C began developing colored bracts earlier than plants grown without RZH. Root-zone heating of 23 to 29 °C also hastened bract anthocyanin production for poinsettia ‘Annette Hegg Brilliant Diamond’ (Janes and McAvoy, 1983). Days to flower for chrysanthemum (*Dendranthema ×grandiflorum* ‘Improved Mefo’) decreased by 13.6 d when plants received RZH of 25 °C (Brown and Ormrod, 1980). Acceleration of maturation has also been reported for tomato (*Lycopersicum esculentum* ‘Jumbo’ and ‘Vendor’) grown with RZH of 26.5 °C, as these plants began producing fruit ≈1 week earlier than plants grown without RZH (Janes et al, 1981). Time to maturation for African violet (*Saintpaulia ionantha* ‘Rapsody’) decreased by 10 to 15% when grown on RZH of 20 to 24 °C compared to 17 °C, with the greatest effect reported during the winter season (Vogelezang, 1988). This suggests a heightened response to RZH with cooler air temperatures. Similarly, flowering of peace lily (*Spathiphyllum* sp. ‘Mauna Loa Brilliant’) was accelerated by 7 or 8 weeks when grown at an air temperature of 17 °C with a RZH set point of 23 or 26 °C, respectively , compared to without RZH (Vogelezang, 1992). Although, when peace lily plants were grown at an air temperature of 20 °C, RZH of 23 °C accelerated flowering by only 1 to 2 weeks (Vogelezang, 1992). Generally, higher root-zone temperatures hasten developmental rates for many crops, especially in combination with reduced air temperatures. This accelerated development is likely due to an increased overall plant temperature.

Altered growth and morphology have also been reported for many crops with varying root-zone temperatures. Hood and Mills (1994) reported a quadratic response in growth, in terms of leaf, stem, and root dry weight and shoot length, for snapdragon 'Peoria' with increasing RZH with maximum growth at a RZH set point of 22 °C. Sweet pepper (*Capsicum annuum* 'Godeon') was reported to have a 7% increase in height when grown in a heated nutrient solution (5 °C warmer) compared to unheated (Abdel-Mawgoud et al., 2005). Conversely, McAvoy and Janes (1984) reported plant heights of 54, 43, and 42 cm with increasing RZH of 17, 23, and 29 °C, respectively, for chrysanthemum 'May Shoesmith' plants grown in day/night air temperatures of 24/17 °C. Higher root-zone temperatures also resulted in smaller flowers of chrysanthemum 'May Shoesmith', decreasing bud diameter by 8.8 cm for plants grown on RZH of 29 °C compared to 17 °C (McAvoy and Janes, 1984). These results likely indicate that 29 °C is a supra-optimal root-zone temperature for chrysanthemum 'May Shoesmith'.

Total biomass accumulation is also affected by root-zone temperature, generally increasing with increased RZH set points up to a species- and cultivar-specific optimum temperature (Shedlosky and White, 1987). Likewise, cooler root-zone temperatures resulted in decreased leaf growth and decreased biomass accumulation for castorbean (*Ricinus communis*); for example, total leaf area was found to be 881, 471, and 288 cm^2 for 20, 15, or 10 °C root-zone temperatures, respectively (Poiré et al, 2010). Final dry mass of French marigold (*Tagetes patula* 'Orange Jubilee'), pansy (*Viola ×wittrockiana* 'Imperial Blue'), petunia 'White Cascade', and snapdragon 'World's Fair White' was significantly greater for plants grown on RZH of 16 or 21 °C compared to without RZH, when grown at night temperatures of 7 °C (Shedlosky and White, 1987). Plants grown

with RZH of 16 or 21 °C and a night temperature of 7 °C had similar dry mass to plants grown without RZH, but a night temperature of 16 °C. For example, final dry mass of pansy ‘Imperial Blue’ and petunia ‘White Cascade’ were 2.4, 2.9, 3.4, or 2.7 g and 3.1, 4.0, 4.6, or 3.7 g for plants grown at a night temperature of 7 °C without RZH or with RZH of 16 or 21 °C, or without RZH at a night temperature of 16 °C, respectively (Shedlosky and White, 1987). Alternatively, a decrease in plant size was reported for chrysanthemum ‘May Shoesmith’ at higher root-zone temperatures; as stem and leaf dry weight decreased by 9% and 42%, respectively, for plants grown with RZH of 29 °C, compared to 17 °C (McAvoy and Janes, 1984).

Overall, increasing root-zone temperatures generally increases growth and rate of development to a species-specific, and even cultivar-specific, optimum; and above the optimum, growth and rate of development declines. Studies on the efficacy of using RZH as an alternative to high air temperatures have become increasingly important as demand for economic and environmental sustainability in the horticulture industry have increased. High and fluctuating energy prices will continue to drive the shift toward alternative and more sustainable greenhouse management practices, which could include the use of reduced air temperatures in combination with RZH for optimizing plant growth and development.

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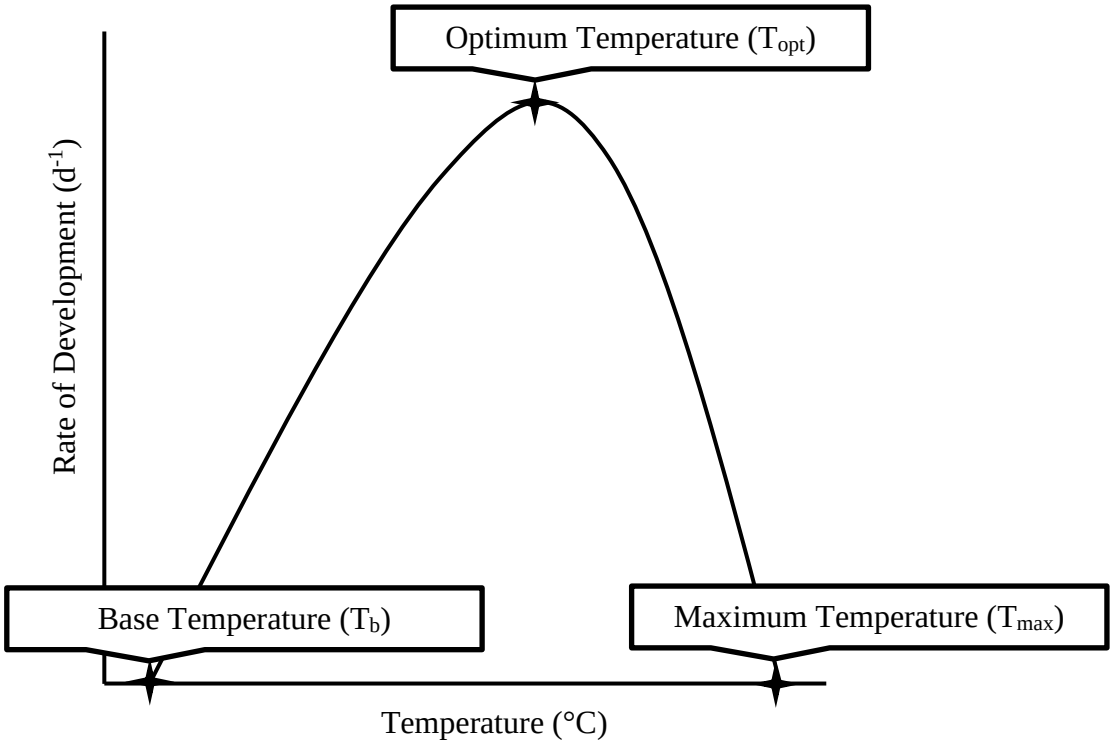

Figure 1.1. Rate of development towards flowering versus temperature. Rate of development towards flowering is zero at the base temperature (T_b), then increases linearly to the optimum temperature (T_{opt}), at which point developmental rate peaks, then decreases rapidly to the maximum temperature (T_{max}), when development again ceases.

GROWTH AND DEVELOPMENT OF POINSETTIA (*EUPHORBIA PULCHERRIMA*) FINISHED UNDER REDUCED AIR TEMPERATURE AND ROOT-ZONE HEATING

Abstract

Greenhouse heating is an essential requirement for holiday poinsettia (*Euphorbia pulcherrima* Willd. ex Klotzsch.) production, especially during the finish stage in northern climates. Previous studies have shown that cultivars with early response attributes (short day initiation to finish in 6 to 8 weeks), moderate to high vigor, and naturally large bracts are most suitable for reduced temperature finishing (RTF) that leads to energy savings. We postulate that RTF in combination with root-zone heating (RZH) can further reduce greenhouse heating costs by allowing for even lower air temperature set points. The objective of this study was to quantify how RTF in combination with bench-top RZH influences growth, development, and quality of six red poinsettia cultivars. Rooted cuttings of poinsettia 'Prestige Early Red', 'Prestige Red', 'Premium Red', 'Infinity Red', 'Viking Red', and 'Bravo Bright Red' were transplanted and grown under a 16-h photoperiod consisting of natural days with day-extension lighting until 01 Oct. and a mean daily temperature (MDT) of 21.5 °C [24/19 °C (12 h day/12 h night)] until 15 Oct. On 15 Oct., air temperature set point was reduced to a MDT of 15 °C [19/13 °C (8 h day/16 h night)], and plants were placed on a bench without RZH or with RZH set points of 21, 24, or 27 °C; or plants were moved into a greenhouse without RZH and with a constant air temperature set point of 21 °C (commercial control). Time

to anthesis from the start of short days was reduced by 6, 4, and 7 d, respectively, for ‘Prestige Early Red’, ‘Premium Red’, and ‘Viking Red’ when plants were finished on a RZH set point of 27 °C compared to a RZH set point of 21 °C. Time to marketability was longer for cultivars grown under RTF without RZH compared to all other treatments. Although plants grown under RTF with RZH matured at a rate similar to those in the commercial control, bract area index was significantly reduced under RTF in most cases. For example, bract area index of ‘Infinity Red’ was reduced by 27, 25, 18, or 19% when finished without RZH in ambient RTF or with a RZH set point of 21, 24, or 27 °C, respectively, compared to the commercial control. Stem-elongation responses varied by cultivar. Our data suggest that when RZH temperatures ≥24 °C are utilized during poinsettia RTF, day/night air temperatures can be further reduced from the 20/13 and 21/17 °C (12 h/12 h), recommended by previous research, to 19/13 °C (8 h/16 h).

Introduction

Poinsettia (*Euphorbia pulcherrima* Willd. ex Klotzsch) continues to be a popular crop during the holiday season in the United States (U.S.) with over 50.4 million pots sold in 2014, totaling $240.9 million USD, and accounting for over 22% of total potted-flowering-plant sales (USDA, 2015a). While this crop remains popular, the wholesale price has risen only 12% in the past 14 years, from an average of $4.21 (USD) in 2000 to $4.73 in 2014, for pots >12.7-cm-diam (USDA, 2001; USDA, 2015b). Meanwhile, prices of natural gas and propane have risen 35 and 70%, respectively, during that time period (EIA, 2015a; EIA, 2015b). As fuel costs have risen, so, too, has the cost of greenhouse heating. Since holiday poinsettia finishing in northern latitudes occurs in the fall, heating

becomes an essential aspect of production, therefore resulting in a major operating cost to the grower.

In order to increase profitability, growers continually look for ways to reduce energy costs. Approaches might include installing thermal energy curtains to deploy at night, increasing insulation, and lowering air temperature set points (Brumfield, 2007). The concept of cold-finishing poinsettia cultivars with early response attributes (initiation to finish in 6 to 8 weeks), moderate to high vigor, and naturally large bracts has been promoted during the past several years (Camberato et al., 2012; Faust and Kehoe, 2007; Lopez, 2008; Lopez and Krug, 2009). However, when air temperatures are reduced during the finish stage of production, delays in crop development and reduced bract area index (BAI) and height have been reported for some cultivars. For example, time to anthesis (TTA) for red poinsettia cultivars increased from 15 to 22 d when day/night air temperature set points during finish were reduced from 24/19 to 20/13 °C (Camberato et al., 2012). Along with this delay, it was reported that height, BAI, and bract area-to-height ratio (BAHR) were reduced across cultivars when plants were finished at day/night temperature set points of 17/17, 19/19, or 16/13 °C, indicating lower quality crops (Camberato et al., 2012). Bract area index of 'Prestige Early Red', 'Advent Red', and 'Viking Red' transplanted during week 33 at Purdue University decreased from 1124 to 910, 1124 to 967, and 1021 to 836 cm^2, respectively, when day/night finish temperatures were reduced from 24/19 to 20/13 °C, respectively (Camberato et al., 2012). Overall, responses were cultivar dependent, but some decrease in crop quality occurred when plants were finished at 20/13 °C compared to 24/19 °C.

Temperature has a direct effect on plant growth, development, and morphology (Blanchard and Runkle, 2011; Kristoffersen, 1969; Vaid and Runkle, 2013). Rate of crop development is directly related to mean daily temperature (MDT) (Blanchard and Runkle, 2011; Vaid and Runkle, 2013). All plant species have a base (T_b), optimum (T_o), and maximum temperature (T_{max}), representing the temperature below which there is no development (T_b), at which there is the maximum developmental rate (T_o), and above which development ceases (T_{max}), respectively (Blanchard and Runkle, 2011). Growers typically use temperature set points between T_b and T_o, and adjust according to the desired finishing time. Base temperature of poinsettia has been estimated to be 10 °C (Berghage et al., 1990). It has been observed that poinsettia 'Dark Red Annette Hegg' was delayed by ≈7 d when finished with split-night air temperatures (7 h and 7 h) of 17 and 11 °C compared to a constant night temperature of 17 °C (Tsujita and Craig, 1980). Additionally, developmental delays due to high ambient air temperatures have been readily observed for poinsettia, which likely would be caused by temperatures above T_o (Wieland et al., 2000; Schnelle et al., 2006). Changes in plant morphology also occur with changes in temperature. For example, temperatures up to 24 °C have been reported to increase stem elongation of poinsettia (Kristoffersen, 1969). Most studies indicate that the difference between day and night temperature (DIF) controls stem elongation and, thus, height (Berghage and Heins, 1991; Moe et al., 1992). Low night temperatures decrease size and number of poinsettia bracts (Tsujita and Craig, 1980).

While previous studies concluded that reduced temperature finishing (RTF) is a viable option for the production of certain red poinsettia cultivars, reducing air temperatures even further may be possible with the use of RZH to maintain or increase

whole plant temperature. Bench-top RZH consists of a series of rubber tubes through which hot water flows. Root-zone heating creates a microenvironment at plant level, raising plant temperature as heat from the bench transfers to the plant and canopy via conduction and convection (Sachs et al., 1992; Vogelezang, 1988; Vogelezang and van Weel, 1989). Increased root-zone temperature without decreased air temperature has been shown to decrease shoot length and hasten plant development for poinsettias (Janes et al., 1981; Wulster and Janes, 1984). Janes and McAvoy (1983) also observed that RZH could remedy the delay of bract coloration that occurred with cool night temperatures alone. It was reported that anthocyanin content of bracts on the main stem was significantly higher for plants grown with a RZH temperature of 26 °C compared to 17 °C. This indicates earlier coloring of the bracts on plants grown with RZH.

To our knowledge, there is no current research on the interaction of reducing air temperature together with RZH for commercially relevant cultivars. Therefore, six commercially important red poinsettia cultivars with attributes reported by Camberato et al. (2012) were selected for this study. The objectives of this study were to 1) quantify how RTF in combination with RZH influences growth, development, and quality of poinsettia cultivars, and 2) determine the effectiveness of using this system to produce compact and marketable poinsettias with reduced energy input for greenhouse heating.

Material and Methods

Plant material and culture. Rooted cuttings of poinsettia ‘Prestige Early Red’, ‘Prestige Red’, ‘Premium Red’, ‘Infinity Red’, ‘Viking Red’, and ‘Bravo Bright Red’ were received at Purdue University, West Lafayette, IN (lat. 40° N) on 06 Aug. 2014

(week 32). Liners of each cultivar were transplanted on 11 Aug. 2014 (week 33) into 1.3 L containers filled with soilless substrate consisting of (by volume) 65% peat, 20% perlite, and 15% vermiculite (Fafard 2 Mix; SunGro Horticulture, Agawam, MA). The apical meristem of each plant was manually excised 14 d after transplant, and 6 nodes were left intact.

Irrigation water was supplemented with 93% sulfuric acid (Brenntag, Reading, PA) at 0.08 $mL \cdot L^{-1}$ to reduce alkalinity to 100 $mg \cdot L^{-1}$ and pH to a range of 5.8 to 6.2. Before 15 Oct., all plants were over-head irrigated, as needed, with alternating clear, acidified water and acidified water supplemented with a combination of two water-soluble fertilizers (3:1 mixture of 15N–2.2P–12.5K and 21N–2.2P–16.6K, respectively; Everris NA, Inc., Marysville, OH) to provide the following (in $mg \cdot L^{-1}$): 200 N, 26 P, 163 K, 50 Ca, 20 Mg, 1.0 Fe, 0.5 Mn and Zn, 0.24 Cu and B, and 0.1 Mo. After 15 Oct., all plants were fertigated once weekly with acidified water supplemented with a combination of two water-soluble fertilizers (3:1 mixture of 15N–2.2P–12.5K and 21N–2.2P–16.6K, respectively; Everris NA, Inc.) to provide the following (in $mg \cdot L^{-1}$): 400 N, 52 P, 326 K, 100 Ca, 40 Mg, 2.0 Fe, 1.0 Mn and Zn, 0.48 Cu and B, and 0.2 Mo. Of the nitrogen provided, 76% was in the form of nitrate (NO_3^-). Plants were irrigated with clear, acidified water as necessary between weekly fertigation events using a fully automated sensor-based irrigation system as described by Ferrarezi et al. (2015). Soil-moisture-sensor probes (10HS; Decagon Devices, Pullman, WA) were inserted diagonally into the medium of one representative plant for each treatment and block. Soil moisture was monitored every 15 min, and if volumetric moisture content fell below the irrigation threshold of 0.25, plants were irrigated through pressure-compensated drip emitters with

acidified water for 30 sec to increase soil moisture content to near water-holding capacity, but not to leaching. Irrigation threshold set point was determined by observing the volumetric moisture content reported by the soil-moisture-sensor probes when plants were in need of watering by personal observation. The intent of this system was to maintain equivalent soil moisture levels and nutrition for plants under all treatments.

Greenhouse environment. Plants were grown at a MDT of 21.5 °C [24/19 °C (12 h day/12 h night; 0800 to 2000 HR)] until 15 Oct. and under a 16-h photoperiod consisting of natural day lengths with day-extension lighting provided from high-pressure sodium (HPS) lamps until 01 Oct. After 01 Oct., an 8-h short day photoperiod was created by covering the benches with an opaque blackout cloth from 1600 to 0800 HR. On 15 Oct., the MDT was reduced to 15 °C [19/13 °C (8 h/16 h; 0800 to 1600 HR)], and RZH treatments were initiated, consisting of plants placed on a bench with RZH set points of 21, 24, 27 °C, or without RZH (ambient). Additionally, a commercial control treatment was established by moving plants to a separate greenhouse without RZH at a constant air temperature set point of 21 °C. A computerized control program (Maximizer Precision 10; Priva Computers Inc., Vineland Station, Ontario, Canada) monitored and regulated air temperature by use of evaporative cooling pads and exhaust fans, hot-water radiant heating, and retractable shade curtains. Root-zone temperatures were achieved using bench-top rubber tubing with circulating hot water (49 °C) controlled by a substrate thermistor probe inserted horizontally in the center of the media (Biotherm Benchwarmer kit; TrueLeaf Technologies, Petaluma, CA).

Environmental data collection. Throughout the study, air temperature for each greenhouse was measured and recorded by a separate aspirated Priva sensor (Maximizer

Precision 10; Priva Computers Inc.). Media temperature was measured using an enclosed thermistor (Model ST-100; Apogee Instruments, Inc., Logan, UT). Plant temperature was determined by injecting a fine-wire thermistor sensor (Model ST-200; Apogee Instruments, Inc.) into the apical meristem. Canopy temperature was measured using an aspirated radiation shield around a thermistor (Model ST-110; Apogee Instruments, Inc.) at plant canopy level. Single-diode quantum sensors (Model LI-190R; LI-COR, Inc., Lincoln, NE) were placed at canopy level to record photosynthetic photon flux (*PPF*). For each treatment and block, media, plant tissue, and canopy air temperatures and *PPF* were measured every 15 s, averaged, and logged every 15 min by a data logger (Model CR1000; Campbell Scientific, Inc., Logan, UT). Mean daily air temperature and daily light integral (DLI) prior to treatment initiation on 15 Oct.; and mean air, canopy, media, plant tissue temperature, and DLI for each treatment each month following treatment initiation are reported in Table 2.1.

Plant data collection and calculations. On 15 Oct., when plants were moved into treatments, initial plant height, measured from the base of the container to the apical meristem, and growth index {GI; [(height + plant width + plant perpendicular width)/3]}, were determined for each plant. Plants were monitored daily to determine time to marketability and anthesis. Marketability was recorded when the bracteoles were fully colored (full ring of colored bracts). Date of anthesis was recorded as the date of visible pollen shed of a cyathium on at least one pseudanthia. At anthesis, plant height and GI were measured. Bract ring diameter and perpendicular diameter of the two largest flowering branches, and stem diameter just below the first branch were also measured and recorded. Roots and stems were excised and dried separately in an oven at 70 ºC.

After 4 d of drying, roots and stems were weighed to determine root dry mass (RDM) and shoot dry mass (SDM). Time to marketability (TTM) and time to anthesis (TTA) were calculated as days from start of short days (01 Oct.) to marketability or anthesis, respectively. The difference between final and initial GI (ΔGI) was used to indicate change in growth from treatment initiation to anthesis. Bract area index was calculated for each pseudanthia as described by Camberato et al. (2012), and the two indices were averaged. Bract area-to-height ratio [BAHR; (BAI/height at anthesis)] was calculated for each plant and used as a measure of aesthetic appeal.

Data analysis. The experiment was a randomized complete block design, with two blocks of the four RZH temperature treatments. Six plants of each cultivar were randomly assigned to each of the treatments within each block. Cultivars were analyzed independently. A separate greenhouse was maintained at a commercial finishing temperature as a control, with 12 plants per cultivar. Analysis of variance was performed using the SAS (SAS 9.4; SAS Institute Inc., Cary, NC) GLM procedure. Experimental error was pooled with plant-to-plant variation. Fisher's protected least significant difference (LSD) was used to compare the four RZH treatments at $P < 0.05$. A *t*-test was used to compare treatment means to the commercial control mean.

Results and Discussion

Time to marketability and time to anthesis. Time to marketability generally decreased with increasing RZH temperatures for all cultivars (Table 2.2). For example, TTM of 'Viking Red' was 58, 56, 55, and 55 d for plants under ambient RTF, or on a RZH set point of 21, 24, or 27 ºC, respectively. Time to marketability for all cultivars on

24 or 27 ºC RZH was not significantly different than TTM for plants in the commercial control. Increased TTM was observed for all cultivars under the ambient RTF without RZH compared to the commercial control. For example, TTM of ‘Prestige Early Red’, ‘Prestige Red’, and ‘Viking Red’ increased by 6, 7, and 3 d, respectively, under ambient RTF compared to the commercial control.

Similar to TTM, TTA also decreased with increasing RZH temperatures (Table 2.2). Time to anthesis from the start of short days was reduced by 4, 6, and 8 d, respectively, for ‘Premium Red’, ‘Prestige Early Red’, and ‘Viking Red’ when plants were finished on a RZH set point of 27 °C compared to plants finished under ambient RTF. Time to anthesis for ‘Viking Red’ was 65, 64, 60, and 57 d for plants finished under ambient RTF, or on a RZH set point of 21, 24, or 27 ºC, respectively. Response to ambient RTF varied by cultivar. Neither ‘Prestige Early Red’ nor ‘Prestige Red’ reached anthesis by 10 Dec. when finished under ambient RTF; while TTA for ‘Premium Red’, ‘Infinity Red’, and ‘Viking Red’ plants under ambient RTF was not significantly different than those under the commercial control.

Time to anthesis for ‘Bravo Bright Red’ was delayed by 3 d when finished under ambient RTF, but hastened by 3 d when finished on a RZH set point of 27 °C, compared to the commercial control. ‘Prestige Early Red’, ‘Infinity Red’, ‘Viking Red’, and ‘Bravo Bright Red’ took significantly less time to reach anthesis when finished with a RZH set point of 27 °C than when finished in the commercial control greenhouse. Clearly, increasing RZH temperature resulted in an increased rate of development.

Root-zone heating is often used to supplement greenhouse heating, especially during certain phases of production, such as propagation. It can be implemented in a

variety of systems, such as hot-water piping embedded in concrete flooring or through rubber tubing circulating hot water on benches. Root-zone heating functions by heating not only the media and root system via conduction, but also the shoots by convection, as heat is transferred to the air around the canopy of the plant (Sachs et al., 1992; Vogelezang, 1988; Vogelezang and van Weel, 1989). Therefore, RZH functions to raise whole plant temperature and, thus, increase rate of development (Blanchard and Runkle, 2011; Vaid and Runkle, 2013).

Under a MDT of 15 °C, an increase in canopy and plant tissue temperature of 4.4 and 4.3 ºC, respectively, were measured in November, when plants were grown at RZH temperatures of 21 to 27 ºC (Table 2.1). An increased rate of development is expected with increased plant temperature, as observed for a variety of floriculture crops. This increased development rate results in decreased time for leaf unfolding, as well as time to flower (TTF). For example, a decrease in MDT from 23 to 14 ºC resulted in an increase in TTF by 105, 53, and 34% for globe amaranth (*Gomphrena globosa* ‘Gnome Purple’), geranium (*Pelargonium* ×*hortorum* ‘Ringo 2000 Deep Red’), and osteospermum (*Osteospermum ecklonis* ‘Asti Purple’), respectively (Vaid and Runkle, 2013). Differences in response to reduced temperature can be attributed to the cold-tolerance of the crop. For example, globe amaranth is a cold-sensitive crop, whereas osteospermum is cold-tolerant. Poinsettia is generally cold-sensitive, further reinforcing the need for careful cultivar selection for RTF.

Time to marketability and TTA findings for the current study are consistent with the findings of Wulster and Janes (1984), who determined that development of poinsettia ‘Brilliant Annette Hegg’ was hastened, in terms of both bract size, color, and pollen shed,

when grown at root-zone temperatures of 29 or 32 °C compared to those grown at a root-zone temperature of 18 °C. Bract anthocyanin content and number of cyathia shedding pollen increased significantly when RZH temperature increased from 18 to 29 °C (Wulster and Janes, 1984). Janes et al. (1981) similarly reported that poinsettia 'Annette Hegg Supreme' and 'V-10' grown at 27 °C root-zone temperatures, began developing colored bracts earlier than plants grown at 18 °C root-zone temperatures. By 1 Nov., bract ring diameter of poinsettia 'V-10' was ≈17 cm for plants with a RZH temperature of 27 °C, compared to ≈8 cm for plants grown with a RZH temperature of 18 °C (Janes et al., 1981). A similar trend of hastened bract development, as early as 3 weeks after treatment initiation, can be observed for 'Infinity Red' (Figure 2.1A). In the current study, TTA decreased by 3 to 6 d when the RZH set point was increased from 21 to 27 °C. Some cultivars matured faster than counterparts in the commercial control when finished on RZH of 24 or 27 °C. An explanation for this response is that tissue temperature at the shoot tip of plants finished on 24 or 27 °C RZH was higher than that in the commercial control (Table 2.1). Similarly, hastened development with increasing RZH temperatures has also been reported with a variety of other horticultural crops, such as chrysanthemum (*Dendranthema ×grandiflorum*), tomato (*Solanum lycopersicum*), African violet (*Saintpaulia ionantha*), and snapdragon (*Antirrhinum majus*) (Brown and Ormrod, 1980; Janes et al, 1981; McAvoy and Janes, 1984; Vogelezang, 1988; Wai and Newman, 1992). Camberato et al. (2012) reported that TTA of poinsettia 'Prestige Early Red', 'Advent Red', and 'Early Orion Red' increased by 19, 16, and 17 d when MDT was reduced by 5 °C. In the current study, when MDT decreased by 6 °C, while some culivars did not reach anthesis by 10 Dec., other cultivars were delayed by only 2 to 3 d.

This variability is due to the variation in cold-tolerance among cultivars. Many modern cultivars have been bred for cold-tolerance, as cold-finishing production regimes have become more popular (Williams, 2009). Plant tissue temperature did not drop as much as the canopy or greenhouse air temperature, reducing the delay in anthesis for some cultivars. The average tissue temperature of plants grown at ambient RTF was between 17.7 and 19.5 °C, while canopy air temperatures were as low as 15.3 to 16.3 °C (Table 2.1). Since a blackout cloth was utilized to create a short day, it also acted much like a thermal energy curtain and helped retain thermal energy from the RZH during the night.

Time to marketability is a representative measure of crop timing for growers. Plants grown in the ambient RTF treatment were delayed 2 to 7 d compared to the commercial control. For all cultivars, TTM was not significantly increased when plants were finished with a RZH set point of 24 or 27 °C, compared to the commercial control. Thus, when MDT is reduced up to 6 °C and a RZH set point of 24 to 27 °C is employed, the poinsettia crop still becomes salable by market date.

Bract Area Index. With the exception of 'Premium Red' and 'Bravo Bright Red', BAI was significantly reduced when plants were finished under RTF with or without RZH, compared to the commercial control (Table 2.2). For example, BAI of 'Infinity Red' was 756, 771, 845, 830, and 1036 cm^2 for plants grown at ambient RTF, on a RZH set point of 21, 24, or 27 °C, and in the commercial control, respectively. Bract area index of 'Premium Red' finished on 27 °C RZH and BAI of 'Bravo Bright Red' finished on 24 and 27 °C RZH was not significantly different than the commercial control.

Reductions in BAI could be of concern to growers as poinsettias are purchased by consumers for their showy colored bracteoles. However, a decrease in BAI did not

necessarily describe the “redness” of the entire plant, as measurements were taken on only the two largest flowering branches. While the commercial control had significantly higher BAIs, it was observed that there were fewer visible bracts above the foliage. Plants finished under RTF had significantly lower BAIs, but more bracts were visible, therefore resulting in a similar level of overall “redness” (Figure 2.1B). This could be attributed to the fact that foliage of the plants under RTF tended to be more compact, therefore allowing for increased visibility of the colored bracts. Dunn et al. (2011) reported that bract number of ‘Winter Blush’, ‘Cortez Burgundy’, ‘Early Orion Red’, ‘Mars Pink’, ‘Enduring White’, and ‘Sonora Red’ increased when grown at day/night air temperatures of 18/15 °C compared to 24/21 °C. Conversely, Camberato et al. (2012) reported a lower BAI under RTF of 20/13 °C or 21/17 °C compared to 24/19 °C for poinsettia ‘Prestige Early Red’, ‘Advent Red’, ‘Orion Red’, ‘EarlyGlory’, ‘Viking Red’, and ‘Christmas Feelings Red’ at one of their locations. They also found that most poinsettia cultivars planted at an earlier transplant date (week 31) and grown at 20/13 °C had a BAI similar to those planted at a later time (week 33) and grown at 24/19 °C. This suggests that a higher BAI could be achieved with an earlier transplant date, while still using RTF with RZH. Similarly, Brown and Ormrod (1980) reported flower diameter of chrysanthemum ‘Improved Mefo’ was reduced when plants were grown with low day/night air temperatures of 16/11 °C without RZH, but this effect was negated when plants were grown on RZH temperatures of 25 °C. Bract-ring diameter of poinsettia ‘Dark Red Annette Hegg’ was reduced 24 to 11% when night temperatures were lowered from 18 to 13 °C anywhere from 4 to 7 weeks after initiation of short days (Tsujita and Craig, 1980).

Bract diameter was also reduced for plants grown with a split night, 7 h at 17 °C and 7 h at 11 °C, compared to a constant 17 °C night (Tsujita and Craig, 1980).

Photothermal ratio, the ratio of radiant energy to thermal energy [moles of photosynthetically active radiation (PAR)/degree-day], rather than temperature alone, has also been proposed as a cause for differences in bract area and inflorescence diameter (Liu and Heins, 2002). One study found that when photothermal ratio increased after short day initiation, bract area and inflorescence diameter of poinsettia 'Freedom' increased by 45 and 23%, respectively. This could be an alternative explanation for the increased BAI of plants in the commercial control, since DLI was higher in that greenhouse, as shown in Table 2.1.

Change in height. Change in height from treatment initiation to anthesis was variable by cultivar (Table 2.2). Increased stem elongation occurred for most cultivars on a RZH set point of 24 or 27 °C relative to ambient RTF. For example, ΔHt of 'Infinity Red' plants increased by 2 or 3 cm when finished on 24 or 27 °C RZH, respectively, compared to ambient RTF (Figure 2.1B). Conversely, there were no significant differences in ΔHt of 'Viking Red' plants; and ΔHt of 'Premium Red' plants was significantly decreased under all RTF treatments compared to the commercial control, regardless of RZH set point.

Plant height of most cultivars generally increased when grown at the higher RZH temperature, as expected. A quadratic response curve of stem elongation with increasing temperature has been determined for poinsettia and snapdragon (Berghage and Heins, 1991; Hood and Mills, 2008). Similarly, stem elongation of sweet pepper (*Capsicum*

annuum ‘Godeon’) also has been reported with increased RZH temperature (Abdel-Mawgoud et al., 2005).

Many studies have also focused on day and night temperature differentials (DIF) as a factor influencing stem elongation (Fisher and Heins, 1995; Moe et al., 1992; Myster and Moe, 1995). Poinsettia ‘Starlight’ plants grown at the same MDT, but with a lower day temperature than night temperature (negative DIF) were ≈5 cm shorter than plants grown with a positive or zero DIF (Moe et al., 1992). Karlsen (1997) reported that stem elongation of young chrysanthemum plants was reduced when grown with a positive or negative root-zone temperature DIF, day/night temperatures of 25/15 °C or 15/25 °C, respectively, compared to plants grown on a constant RZH temperature of 20 °C. This reduction was proposed to result from a shift in stem pressure potential with the change in temperature in the morning. In the current study, all treatments had a constant root-zone temperature, so DIF would not likely have caused the observed ΔHt. In a study of eight poinsettia cultivars finished under RTF, it was reported that MDT rather than DIF had the greatest effect on final height (Camberato et al., 2012). Tsujita and Craig (1980) also observed decreased height for poinsettia ‘Dark Red Annette Hegg’ plants when they were finished with decreased night temperatures from 17 to 11 °C for half the night (7 h) compared to a constant 17 °C night. In the current study, most plants grown with 24 or 27 °C RZH had ΔHt comparable to the commercial control, and almost all cultivars grown in the ambient RTF had reduced ΔHt compared to the commercial control. This is consistent with the findings of Kristoffersen (1969), who reported poinsettia ‘Viking’ and ‘Paul Mikkelsen’ had a 5-fold increase in the rate of stem elongation when grown at a constant air temperature of 24 °C compared to plants grown at 15 °C (Kristoffersen, 1969). A

decrease in stem elongation, as observed for most plants finished under RTF, can be valuable, as it could alleviate the need for plant-growth-regulator applications (Kristoffersen, 1969).

Bract area-to-height ratio. The response of BAHR was cultivar dependent, with significant differences between RTF treatments occurring only for 'Viking Red' (Table 2.2). Bract area-to-height ratio of 'Viking Red' plants was highest, similar to plants under the commercial control, when plants were finished on a RZH set point of 21 °C. 'Prestige Red' plants finished on a RZH set point of 21 °C also had a similar BAHR to plants under the commercial control. Conversely, 'Premium Red' plants had a significantly lower BAHR when finished on 21 °C RZH, but a BAHR similar to that of the commercial control when finished on a RZH set point of 27 °C.

Bract area-to-height ratio, used as a measure of aesthetic appeal (Currey and Lopez, 2011), did not follow a common trend between cultivars. This inconsistency is likely caused by the variance in BAI and height between cultivars. Camberato et al. (2012) reported increased BAHR with increased day/night temperatures from 20/17 °C to 24/19 °C. In the current study, most cultivars grown at ambient RTF had decreased BAHR, but the RZH temperature set point resulting in the highest BAHR was cultivar dependent (Table 2.2).

Change in growth index. In the current study, all cultivars, with the exception of 'Prestige Red', had growth comparable to the commercial control when finished on a RZH set point of 27 °C; though ΔGI, used as a measure of overall growth, varied by cultivar. Generally, increased growth occurred at higher RZH temperatures (Table 2.2). For example, the ΔGI of 'Prestige Early Red' was 5.9, 7.8, 8.9, or 9.3 cm when finished

under ambient RTF or with a RZH set point of 21, 24, or 27 °C, respectively. Growth of ‘Prestige Early Red’ on the 24 and 27 °C RZH set points was similar to plants under the commercial control with ΔGIs of 8.9, 9.3, and 8.9 cm, respectively. ‘Prestige Red’, ‘Infinity Red’, ‘Viking Red’, and ‘Bravo Bright Red’ had the greatest mean ΔGI when finished on a RZH set point of 24 °C. This could indicate some growth inhibition under the highest RZH set point. ‘Prestige Red’ had a significantly lower ΔGI when finished on 27 °C RZH compared to the commercial control. A similar inhibition was also observed for poinsettia ‘Annette Hegg Brilliant Diamond’, as a ≈25% decrease in growth was reported for plants grown on 29 °C RZH compared to plants on RZH of 23 and 26 °C (Janes and McAvoy, 1983). In contrast, Wulster and Janes (1984) reported an increase in growth, in terms of axillary shoot length, for poinsettia ‘Brilliant Annette Hegg’ plants grown continuously on a RZH set point of 32 °C, compared to plants grown without RZH.

Shoot and root dry mass. All cultivars under the RTF treatments had significantly reduced SDM compared to those in the commercial control (Table 2.2). ‘Premium Red’ and ‘Viking Red’ plants had significantly higher SDM at anthesis when finished under ambient RTF compared to those grown on RZH. For example, SDM of ‘Viking Red’ was 18.0 g/plant for plants finished under ambient RTF, but only 14.7 g/plant for plants finished with a RZH set point of 27 °C. However, this increase in SDM can be attributed to the fact that those plants took an average of 8 d longer to reach anthesis and, thus, had more time to accumulate biomass prior to harvest. No significant differences occurred for RDM of any cultivars between RTF treatments. ‘Prestige Red’, ‘Premium Red’, and ‘Bravo Bright Red’ plants grown under ambient RTF had a reduced RDM compared to

the commercial control. Root dry mass of ‘Prestige Red’, ‘Premium Red’, and ‘Viking Red’ was also reduced when finished on a RZH set point of 27 °C compared to the commercial control. This reduction in RDM could be caused by root growth inhibition at the highest RZH set point, which could be due to increased respiration rate. Dark respiration has been reported to increase exponentially with increasing temperatures from 6 to 36 °C (van Iersel, 2003). It also could be attributed to the fact that plants grown on 27 °C RZH matured earlier and, thus, had less time to accumulate biomass before harvest.

The highest leaf dry mass for poinsettia ‘Annette Hegg Brilliant Diamond’ was reported when plants were grown at a 23 °C root-zone temperature, compared to plants grown on 15, 18, or 29 °C root-zone temperatures (Wulster and Janes, 1984). A decrease in leaf and main stem dry mass for poinsettia ‘V-10’, ‘Annette Hegg Supreme’, and ‘Annette Hegg Brilliant Diamond’ plants was also reported when plants were grown at 32 °C root-zone temperature compared to 17 °C RZH (Wulster and Janes, 1984). At supra-optimal RZH temperatures of 25 to 40 °C, total plant dry mass of pepper ‘Jun Jiao No. 3’ decreased, along with water potential and stomatal conductance, compared to a constant 20 °C RZH temperature (Dodd et al., 2000). These studies substantiate the concept that growth inhibition can occur at high RZH temperature set points.

Abdel-Mawgoud et al. (2005) reported that sweet pepper ‘Godeon’ had increased dry mass with a RZH temperature increase of 5 °C, from 15 to 20 °C. Shoot dry mass of tomato ‘Vendor’ plants has also been reported to increase 15, 37, or 80% with increased RZH temperatures from 12 to 24 °C, when grown under natural light, an 8-h photoperiod, or a 12-h photoperiod, respectively (Gosselin and Trudel, 1984). This indicates that

changes in dry mass accumulation could be the result of an interaction between RZH temperature and light intensity. Liu and Heins (2002) found that dry mass accumulation by poinsettia ‘Freedom’ increased linearly as the photothermal ratio increased after short day initiation. Incidentally, increasing temperature would cause a decrease in the photothermal ratio, which could also be a cause of decreased SDM for the plants subjected to the highest RZH temperature in the current study.

Stem diameter. Differences in stem diameter between treatments varied by cultivar (Table 2.2). Average stem diameter of ‘Prestige Early Red’ plants was significantly higher when finished with a RZH set point of 24 or 27 °C, compared to either ambient RTF or a 21 °C RZH set point. All ‘Premium Red’ plants under RTF had a smaller stem diameter than the commercial control. Conversely, ‘Infinity Red’ plants had an increased stem diameter when finished on 27 °C RZH temperature compared to the commercial control, while all other treatments were comparable to the commercial control. Liu and Heins (2002) found that photothermal ratio was positively correlated with stem diameter of poinsettia ‘Freedom’. Photothermal ratio prior to short day initiation was most influential in this correlation. An increase in photothermal ratio during the reproductive stage from 0.02 to 0.06 mol/degree-day resulted in an increase in stem diameter of 0.7 mm (Liu and Heins, 2002). Since all plants in the current study were grown under the same conditions prior to short day initiation, the photothermal ratio likely had minimal effect on stem diameter. Contrary to the findings of the current study, Brown and Ormrod (1980) reported an increase in stem diameter for chrysanthemum ‘Nobhill’ and ‘Early Golden Hill’ plants grown with RZH temperatures of 25 °C with

cool day/night air temperatures of 16/11 °C, compared to plants grown at higher air temperatures of 20/16 °C.

Conclusion

Our results indicate that RTF for poinsettia production with a 24 or 27 °C RZH set point is an effective means to produce high-quality, marketable, potted poinsettia plants. While some morphological effects were observed, such as decreased height and BAI under RTF for some cultivars, overall quality and marketability of plants was not adversely affected. Time to marketability and TTA was comparable or slightly decreased for all cultivars when a 27 °C RZH set point was employed. Time to anthesis for 'Prestige Red' was delayed by 3 d when grown at a RZH set point of 24 °C compared to the commercial control, but all other cultivars had a similar TTA to the commercial control when grown on a RZH temperature of 24 °C. Since the 24 °C RZH set point would require less energy input and avoided the growth inhibition that occurred for some cultivars at the highest temperature set point, this would likely be a target temperature set point to employ. Cultivar variation in cold-tolerance and response to RZH has been observed in this study and previously (Camberato et al., 2012; Dunn et al., 2011). Hence, careful cultivar selection should be used when implementing cold-finishing and use of RZH. Some research has shown that selection of cold-tolerant cultivars for cold-finishing can allow for up to 35% more fuel-efficient production (Williams, 2009). Therefore, further studies with additional poinsettia cultivars and bract colors, such as pink and white, will be necessary before a grower fully transitions to this method of production. Now that proof-of-concept of this method for production has been established, energy

evaluations for costs and savings of using this system should also be explored in further studies. Overall, results from the current study suggest that day/night air temperatures can be maintained at 19/13 °C if a RZH set point of 24 to 27 °C is utilized during the finish stage of poinsettia production.

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Table 2.1. Mean daily air temperature (MDT) and daily light integral (DLI) prior to treatment initiation on 15 Oct.; and mean DLI and air, canopy, media, and plant tissue temperature for each treatment for each month following treatment initiation. Plants were grown at a MDT of 21.5 °C [day/night 24/19 °C (12 h/12 h; 0800 to 2000 HR)]. After 15 Oct., the air temperature was reduced to a MDT of 15 °C [19/13 °C (8 h/16 h; 0800 to 1600 HR)] and plants were placed on a bench without root-zone heating (RZH) (Ambient) or with RZH set points of 21, 24, or 27 °C; or plants were moved to a greenhouse without RZH and an air temperature set point of 21 °C as per commercial practice (Comm.).

		Mean DLI	Temperature (°C)			
Month	Treatment	($mol \cdot m^{-2} \cdot d^{-1}$)	Air	Canopy	Media	Tissue
Aug.	—[z]	12.1	23.6	—	—	—
Sept.	—	11.1	22.2	—	—	—
01 to 14 Oct.	—	6.1	22.1	—	—	—
15 to 31 Oct.	Ambient	5.3	16.3	19.0	18.7	19.5
	21 °C RZH	4.2	16.3	19.9	22.1	19.5
	24 °C RZH	5.4	16.3	21.9	25.7	21.4
	27 °C RZH	5.8	16.3	23.4	28.5	23.4
	Comm.	9.5	20.5	19.9	19.8	19.3
Nov.	Ambient	5.6	15.4	17.7	16.9	18.6
	21 °C RZH	4.5	15.4	19.2	23.5	18.9
	24 °C RZH	4.0	15.4	21.7	22.6	21.1
	27 °C RZH	4.3	15.4	23.6	27.2	23.2
	Comm.	6.5	21.1	19.4	18.7	19.5
Dec.	Ambient	3.5	15.3	20.0	16.7	17.7
	21 °C RZH	3.2	15.3	21.3	19.4	20.5
	24 °C RZH	3.3	15.3	23.5	24.5	22.1
	27 °C RZH	3.0	15.3	22.8	26.8	25.0
	Comm.	4.6	20.0	18.2	17.5	18.5

[z] Treatments initiated on 15 Oct., thus, data were not separated by treatment.

Table 2.2. Time to marketability (TTM), time to anthesis (TTA), bract area index (BAI), determined by using the formula for an ellipse [(widest diameter × perpendicular diameter × π) / 4], change in height from treatment initiation to anthesis (ΔHt), bract area-to-height ratio (BAHR), determined as BAI/final height at anthesis, change in growth index (plant height + width + perpendicular width / 3) from treatment initiation to anthesis (ΔGI), shoot and root dry mass (SDM; RDM), and stem diameter (SD) just below the first branch of poinsettia 'Early Prestige Red', 'Prestige Red', 'Premium Red', 'Infinity Red', 'Viking Red', and 'Bravo Bright Red'. Plants were grown at a mean daily temperature (MDT) of 21.5 °C [day/night 24/19 °C (12 h/12 h; 0800 to 2000 HR)]. After 15 Oct., the air temperature was reduced to a MDT of 15 °C [19/13 °C (8 h/16 h; 0800 to 1600 HR)] and plants were placed on a bench without root-zone heating (RZH) (Ambient) or with RZH set points of 21, 24, or 27 °C; or plants were moved to a greenhouse without RZH and an air temperature set point of 21 °C (Comm.).

Treatment	TTM (d)	TTA (d)	BAI (cm^2)	ΔHt (cm)	BAHR ($cm^2 \cdot cm^{-1}$)	ΔGI (cm)	SDM (g)	RDM (g)	SD (mm)
				'Early Prestige Red'					
Ambient	†62.6 a	—[y]	†657	†4.9 b	†18.8	†5.9 c	†17.4	2.8	†7.9 b
21 °C RZH	58.3 b	66.7 a	†717	†6.3 a	†20.0	†7.8 b	†16.1	2.6	†7.7 b
24 °C RZH	57.8 b	64.4 a	†761	6.4 a	21.2	8.9 ab	†15.8	2.9	†8.4 a
27 °C RZH	57.6 b	†60.9 b	†730	7.2 a	†20.1	9.3 a	†15.5	2.7	8.4 a
Comm.	57.1	65.8	824	7.3	22.2	8.9	19.8	2.9	8.7
Significance	**	*	NS	*	NS	***	NS	NS	**
				'Prestige Red'					
Ambient	†63.0 a	—	†639	†5.6	†18.2	†5.9 b	†16.8	†2.1	†7.8
21 °C RZH	†59.7 b	†66.4 a	†723	†6.1	20.2	7.3 b	†17.0	2.8	†8.1
24 °C RZH	58.3 b	†64.5 ab	†719	7.3	†19.6	9.3 a	†16.9	2.8	8.6
27 °C RZH	57.5 b	62.0 b	†704	†6.7	†19.1	†7.1 b	†15.6	†2.5	†8.4
Comm.	56.3	61.9	823	7.8	21.8	8.4	20.4	3.2	9.1
Significance	**	*	NS	NS	NS	**	NS	NS	NS
				'Premium Red'					
Ambient	†58.5 ab	62.8 a	†652	†6.2	18.9	†4.6	†15.9 a	†1.4	†7.5
21 °C RZH	†60.1 a	63.4 a	†637	†7.2	†17.4	5.8	†14.7 ab	†1.5	†7.3

Table 2.2 Cont.

24 °C RZH	56.6 bc	60.3 ab	†630	†7.7	†17.7	6.3	†12.4 c	1.8	†7.5
27 °C RZH	54.8 c	59.3 b	705	†7.8	20.0	6.4	†13.5 bc	†1.5	†7.5
Comm.	54.9	60.9	717	8.9	20.0	6.6	17.8	1.9	8.0
Significance	**	*	NS	NS	NS	NS	*	NS	NS
				‘Infinity Red’					
Ambient	†58.7	66.8	†756	†6.1 b	†19.4	†3.2 b	†19.1	1.6	7.0
21 °C RZH	†59.1	68.7	†771	8.0 ab	†19.9	5.2 ab	†17.5	1.7	7.0
24 °C RZH	56.5	†65.4	†845	9.2 a	†21.1	†6.1 a	†16.3	†1.5	7.2
27 °C RZH	56.4	†65.1	†830	8.2 a	†21.3	5.3 ab	†16.7	1.6	†7.4
Comm.	54.9	67.1	1036	8.8	25.9	4.9	22.7	1.9	7.0
Significance	NS	NS	NS	*	NS	*	NS	NS	NS
				‘Viking Red’					
Ambient	†58.3 a	64.5 a	†734	5.8	†19.6 ab	†5.4 b	†18.0 a	1.5	†7.0
21 °C RZH	56.4 b	63.7 a	†767	5.6	20.7 a	6.9 a	†16.1 ab	1.6	7.6
24 °C RZH	54.7 bc	†59.7 b	†707	6.1	†18.6 b	8.2 a	†14.9 b	1.8	†7.5
27 °C RZH	54.6 c	†56.8 c	†695	5.8	†19.0 b	7.0 a	†14.7 b	†1.4	7.8
Comm.	55.3	62.5	814	6.4	21.6	7.6	20.5	1.8	8.0
Significance	***	***	NS	NS	*	***	*	NS	NS
				‘Bravo Bright Red’					
Ambient	†59.1 ab	†67.0 a	†719	†6.3	19.8	†4.9 b	†16.5	†1.9	†8.0
21 °C RZH	†60.6 a	63.7 ab	†684	†6.6	†18.7	5.7 ab	†15.9	2.4	†8.2
24 °C RZH	56.5 bc	62.5 b	756	8.0	20.3	7.4 a	†15.4	2.5	8.5
27 °C RZH	55.9 c	†60.8 b	764	7.1	20.2	6.6 a	†16.0	2.6	†8.2
Comm.	56.5	63.8	794	8.0	21.1	6.5	18.8	2.5	8.7
Significance	**	**	NS	NS	NS	*	NS	NS	NS

† indicates significant difference from commercial control (Comm.) based on LSD at $P \leq 0.05$.

NS, *, **, or *** indicates treatments (Ambient, 21, 24, or 27 °C RZH) not significant or significant at $P \leq 0.05$, .01, or .001, respectively.

z Means within column with the same letter are not significantly different based on Fisher’s protected LSD at $P \leq 0.05$.

y – indicates that plants did not reach anthesis by 10 Dec.

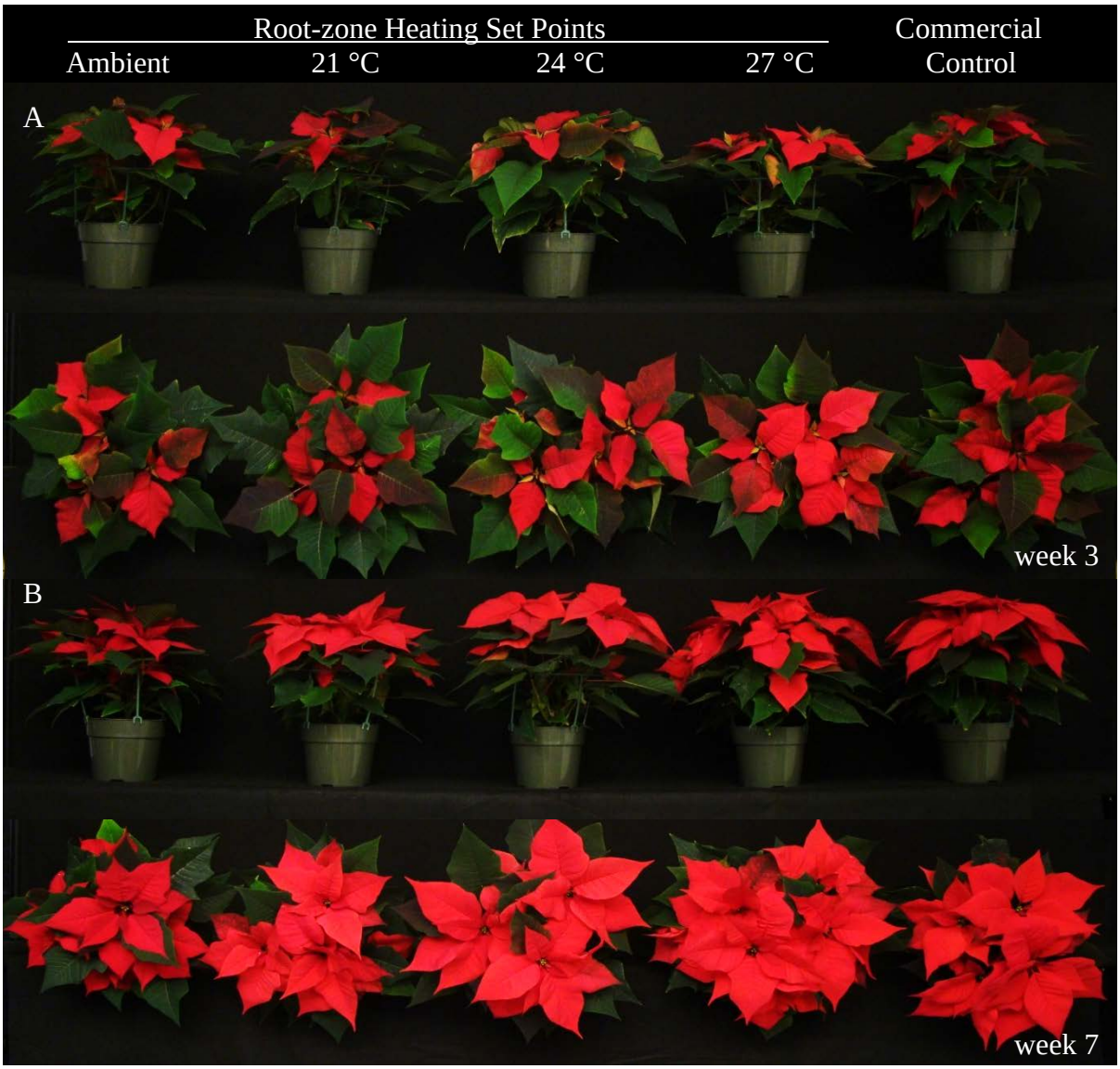

Figure 2.1. Poinsettia ‘Infinity Red’ at 3 (A) and 7 (B) weeks after treatment initiation. Plants were grown at a mean daily temperature (MDT) of 21.5 °C [day/night 24/19 °C (12 h/12 h; 0800 to 2000 HR)]. After 15 Oct., the air temperature was reduced to a MDT of 15 °C [19/13 °C (8 h/16 h; 0800 to 1600 HR)] and plants were placed on a bench without root-zone heating (RZH) (Ambient) or with RZH set points of 21, 24, or 27 °C; or plants were moved to a greenhouse without RZH and an air temperature set point of 21 °C (Commercial Control).

ROOT-ZONE HEATING HASTENS DEVELOPMENT OF PETUNIA UNDER A REDUCED AIR TEMPERATURE

Abstract

Heating accounts for up to 30% of total operating costs for greenhouse operations at northern latitudes. Growers often lower air temperatures for production to reduce energy costs; however, this causes delays in development, even in cold-tolerant crops such as petunia (*Petunia ×hybrida*). This delay increases production time and can reduce grower profitability. Recent studies of reduced temperature bedding plant production indicate petunia as a strong potential candidate for production using reduced air temperature in combination with bench-top root-zone heating (RZH) to prevent or reduce delays in development. The objectives of this study were to: 1) quantify time to flower (TTF) of seven petunia cultivars and two recombinant inbred lines (RILs) when the mean daily air temperature (MDT) was reduced by 5 °C and bench-top RZH was utilized, and 2) determine if a high-quality petunia crop can be produced using RZH. Petunia 'Sun Spun Burgundy', 'Sun Spun Lavender Star', 'Sanguna Patio Red', 'Potunia Plus Red', 'Potunia Plus Purple', 'Supertunia Red', 'Supertunia Bordeaux', and two RILs IA160 and IA349, were grown in a greenhouse with a MDT of 15 °C without RZH or with a RZH set point of 21, 24, or 27 °C. Additionally, a commercial control was established by growing plants in a separate greenhouse without RZH at a MDT of 20 °C. All plants were grown under a 16-h photoperiod with day-extension lighting provided from high-pressure sodium lamps to provide a daily light integral of 10 to 12 $mol \cdot m^{-2} \cdot d^{-1}$.

As RZH temperature increased, TTF decreased for all plants. For example, TTF of ‘Potunia Plus Red’ was 56, 52, 49, or 47 d for plants grown at a MDT of 15 °C without RZH, or with RZH set points of 21, 24, or 27 °C, respectively. When a RZH set point of 27 °C was employed, TTF of all cultivars and RILs, except ‘Potunia Plus Red’ and ‘Sanguna Patio Red’, was similar to that of plants grown at a MDT of 20 °C. Reduced stem length, growth index, and shoot dry mass at flowering were observed for plants grown under reduced air temperatures with RZH, resulting in a more compact and high-quality plant. For example, stem length was reduced by 4.1, 5.3, and 8.5 cm for ‘Supertunia Red’, IA160, and IA349, respectively, grown at a MDT of 15 °C with a RZH set point of 27 °C compared to without RZH. Producing a compact plant in a shorter time period is beneficial for growers; thus, results suggest that MDT can be reduced to 15 °C for petunia production when a RZH set point of 27 °C is employed.

Introduction

Greenhouse heating currently accounts for up to 30% of total operating cost for growers in northern latitudes (Lopez and Runkle, 2014). Growers are therefore continually looking for ways to produce high-quality bedding plants through late winter and early spring with reduced energy inputs for heating, by installing thermal energy curtains, purchasing more efficient heaters or boilers, increasing insulation, or lowering air temperature set points for production (Brumfield, 2007; Runkle and Both, 2011). When mean daily air temperature (MDT) set points are lowered, the rate of flowering is often delayed (Blanchard and Runkle, 2011). Although growers correlate reduced temperatures to energy-cost savings, these delays due to increased production time can

often increase production costs or lead to missed market dates (Blanchard et al., 2011b). Recent studies investigating the effects of low-temperature production in greenhouses and high tunnels indicate that flowering of cold-tolerant crops, such as petunia (*Petunia ×hybrida*), is delayed by 19 to 32 d when air temperature is reduced by 9 to 12 ºC (Blanchard et al., 2011a; Blanchard et al., 2011b; Currey et al., 2014; Gerovac et al., 2015). However, Gerovac (2014) reported that the flowering of seed-propagated petunia 'Dreams Midnight' was only delayed by 4 d when grown at a MDT of 16 ºC in combination with bench-top root-zone heating (RZH) of 27 ºC compared to a MDT of 19 ºC without RZH.

Petunia is one of the most prominent and popular bedding plants in the United States. Total value of this crop was over $262 million in 2014, with ≈25 million potted petunias sold in the top 15 producing states (USDA, 2015a; USDA, 2015b). Petunia has a reported optimum temperature (T_{opt}) of ≈25 °C, at which the rate of development is most rapid, and a calculated base temperature (T_b) of 1.5 °C, at which development ceases (Kaczperski et al., 1991; Warner, 2010). Plants are generally categorized based on T_b as cold-tolerant, cold-intermediate, or cold-sensitive, when $T_b \leq 4$, $4 < T_b < 7$, or $T_b \geq 7$, respectively (Blanchard and Runkle, 2011) A linear increase in the rate of plant development is generally observed in the range between T_b and T_{opt} (Adams et al., 1998). Growers, therefore, select temperature set points within this range and adjust for desired market dates and finished plant quality. While growing at the T_{opt} may produce a crop most rapidly, a decrease in quality is often observed (Blanchard et al., 2011b). Overall, as MDT increases, rate of crop development increases, up to the T_{opt}.

Adams et al. (1998) reported that, under natural photoperiods, petunia ‘Express Blush Pink’ grown at 22 or 25 °C flowered 43 d faster than if grown at 15 °C. Similarly, Blanchard et al. (2011b) found that under a 16-h photoperiod, time to flower (TTF) of petunia ‘Dreams Neon Rose’ was hastened by 19 d as MDT increased from 14 to 26 °C. Petunias are a long-day plant; therefore, rate of development is also hastened by increasing photoperiod up to a critical photoperiod of 14.4 ± 0.6 h·d^{-1}, although this can vary by cultivar (Adams et al., 1998).

Root-zone heating has been found to be an efficient method of increasing rate of development for a variety of crops, including verbena (*Verbena ×hybrida*), petunia, poinsettia (*Euphorbia pulcherrima*), chrysanthemum (*Dendranthema ×grandiflorum*), tomato (*Solanum lycopersicum*), African violet (*Saintpaulia ionantha*), and snapdragon (*Antirrhinum majus*) (Brown and Ormrod, 1980; Gerovac, 2014; Janes et al, 1981; McAvoy and Janes, 1984; Olberg and Lopez, unpublished data; Vogelezang, 1988; Wai and Newman, 1992). For example, Gerovac (2014) reported that verbena ‘Aztec Blue Velvet’ took 18 d longer to flower at a MDT of 16 °C when grown without RZH, compared to when grown with a RZH set point of 27 °C. Bench-top RZH functions by circulating hot water through a series of rubber tubes on top of the bench. Potted crops are then placed into trays directly on the rubber tubes, allowing heat to transfer to the media, root system, and shoots via conduction, and into the canopy by convection as heat rises from the bench, creating a microclimate within the crop canopy (Sachs et al., 1992; Vogelezang, 1988; Vogelezang and van Weel, 1989).

The effect of MDT on petunia has been studied extensively, but to our knowledge, there has been little research on the effect of increased root-zone temperature

in combination with a reduced air temperature on petunia cultivars and recombinant inbred lines (RILs). Commercially available, vegetatively-propagated petunia cultivars were all selected based on breeder input for cold-tolerance and vigorous growth; and the RILs selected were specifically bred for cold-tolerance. The objectives of this study were therefore to: 1) quantify TTF of seven petunia cultivars and two RILs when the MDT was reduced by 5 °C and bench-top RZH was utilized and 2) determine if a high-quality petunia crop could be produced with RZH.

Materials and Methods

Plant material and culture. Rooted cuttings of petunia 'Sun Spun Burgundy', 'Sun Spun Lavender Star', 'Sanguna Patio Red', 'Potunia Plus Red', 'Potunia Plus Purple', 'Supertunia Red', and 'Supertunia Bordeaux' and seedlings of two RILs derived from the interspecific cross *P. integrifolia* × *P. axillaris* (crossed at Michigan State University), IA160 and IA349, were received at Purdue University, West Lafayette, IN (lat. 40° N) between 13 Jan. and 20 Jan. 2015 (Week 2 or 3). The RILs were selected based on exhibiting: 1) a relatively high development rate under cool (14 °C) temperature and 2) a minimal reduction in development rate as temperature decreased from 20 to 14 °C, from among the total population of ≈150 RILs evaluated previously (Lin, 2014). The apical meristem of each 'Sun Spun Burgundy', 'Sun Spun Lavender Star', 'Sanguna Patio Red', 'Potunia Plus Red', and 'Potunia Plus Purple' plant was excised (pinched) on 19 Jan. 2015. The apical meristem of each 'Supertunia Red' and 'Supertunia Bordeaux' plant was excised (pinched) on 20 Jan. 2015. On 20 Jan. 2015, Ethephon (Florel; Monterey, Fresno, CA) with a surfactant (Capsil; Aquatrols, Paulsboro, NJ) was applied

as a foliar spray at a concentration of 400 $mg \cdot L^{-1}$ and a volume of 0.2 $L \cdot m^{-2}$ to abort and abscise all premature flowers and flower buds. All plants were transplanted on 21 Jan. 2015 into 11.4-cm (600 mL) containers filled with soilless substrate consisting of (by volume) 65% peat, 20% perlite, and 15% vermiculite (Fafard 2 Mix; SunGro Horticulture, Agawam, MA).

Irrigation water was supplemented with 93% sulfuric acid (Brenntag, Reading, PA) at 0.08 $mL \cdot L^{-1}$ to reduce alkalinity to 100 $mg \cdot L^{-1}$ and maintain a pH within the range of 5.8 to 6.2. All plants were fertigated once weekly with acidified water supplemented with a combination of two water-soluble fertilizers (3:1 mixture of 15N–2.2P–12.5K and 21N–2.2P–16.6K, respectively; Everris, Marysville, OH) to provide the following (in $mg \cdot L^{-1}$): 400 N, 52 P, 326 K, 100 Ca, 40 Mg, 2.0 Fe, 1.0 Mn and Zn, 0.48 Cu and B, and 0.2 Mo. All plants were over-head irrigated with clear acidified water as necessary between fertigation events to maintain equivalent substrate moisture and nutrition levels among all treatments.

Greenhouse environment. Plants were grown in two separate glass-glazed greenhouses. In both greenhouses, a 16-h photoperiod (0600 to 2200 HR) was established consisting of natural day lengths with day-extension and supplemental lighting provided by high-pressure sodium (HPS) lamps that delivered 70 $\mu mol \cdot m^{-2} \cdot s^{-1}$, set to turn on between 0600 and 2200 HR when ambient outdoor light levels were <800 $\mu mol \cdot m^{-2} \cdot s^{-1}$, to achieve a total daily light integral (DLI; ambient plus supplemental light) of ≈10 to 12 $mol \cdot m^{-2} \cdot d^{-1}$. A computerized control program (Maximizer Precision 10; Priva Computers Inc., Vineland Station, Ontario, Canada) monitored, controlled, and recorded greenhouse

air temperature. Greenhouse air temperature was regulated by use of evaporative cooling pads and exhaust fans, hot-water radiant heating, and retractable shade curtains.

Temperature treatments were initiated on 22 Jan. 2015. The air temperature set point was a constant MDT of 15 °C, and plants were placed onto benches with or without independently programmable bench-top RZH. Root-zone temperatures of 21, 24, and 27 °C were established with circulating hot water (49 °C) though rubber tubing on the benches, controlled by a root-zone thermistor probe inserted horizontally at the center of the media (Biotherm Benchwarmer kit; TrueLeaf Technologies, Petaluma, CA). A separate greenhouse served as a commercial control and with a MDT of 20 °C without RZH.

Environmental data collection. Throughout the study, air temperature was measured every 10 min by an aspirated Priva temperature sensor and recorded by the computerized control system (Priva Computers Inc.) in each greenhouse. An enclosed thermistor (Model ST-100; Apogee Instruments, Inc., Logan, UT) inserted horizontally into the center of the media was used to measure media temperature. A fine-wire thermistor (Model ST-200; Apogee Instruments, Inc.) was inserted into the apical meristem of one plant per treatment and block on 05 Feb. to measure plant tissue temperature. A thermistor (Model ST-110; Apogee Instruments, Inc.) surrounded by an aspirated radiation shield suspended at plant canopy level measured canopy air temperature. Single-diode quantum sensors (Model LI-190R; LI-COR, Inc., Lincoln, NE) were placed at canopy level to record photosynthetic photon flux (*PPF*) in each treatment and block. For each treatment and block, media, plant tissue, and canopy air temperatures and *PPF* were measured every 15 s, averaged, and logged every 15 min by a data logger

(Model CR1000; Campbell Scientific, Inc., Logan, UT). Mean greenhouse air, canopy, media, and plant tissue temperature and DLI for each treatment, each month following transplant, are reported in Table 3.1.

Plant data collection and calculations. Plants were monitored daily and the date of first open flower was recorded when the first flower was fully reflexed. At flowering, node number below the first open flower and stem length from the base of the plant to the apical meristem were measured. Branch number was also recorded for petunia IA160, IA349, 'Supertunia Red', and 'Supertunia Bordeaux'; and plant width and perpendicular width were recorded for petunia 'Sun Spun Burgundy', 'Sun Spun Lavender Star', 'Sanguna Patio Red', 'Potunia Plus Red', and 'Potunia Plus Purple'. Growth index [GI; (stem length + plant width + plant perpendicular width)/ 3] was then calculated for petunia 'Sun Spun Burgundy', 'Sun Spun Lavender Star', 'Sanguna Patio Red', 'Potunia Plus Red', and 'Potunia Plus Purple'. Roots of 'Sun Spun Lavender Star', 'Supertunia Bordeaux', 'Potunia Plus Purple', and IA349 were washed and shoots of all plants were excised and dried separately in an oven at 70 ºC. After 4 d of drying, roots and shoots were weighed to determine root dry mass (RDM) and shoot dry mass (SDM), respectively. Time to flower was calculated as days from transplant (21 Jan.) to first open flower. Root-to-shoot ratio (RDM/SDM) was calculated for 'Sun Spun Lavender Star', 'Supertunia Bordeaux', 'Potunia Plus Purple', and IA349.

Experimental design and data analysis. The experiment was a complete randomized design, with two blocks of each reduced air temperature treatment. Ten experimental units (single plants of each cultivar or RIL) were randomly distributed to each treatment within each block. Cultivars and RILs were analyzed independently. A

separate greenhouse served as a commercial control and was maintained at a commercial finishing temperature with two blocks, each containing ten experimental units. Analysis of variance was performed using the SAS (SAS 9.4; SAS Institute Inc., Cary, NC) mixed-model (PROC MIXED) procedure. Fisher's protected least significant difference (LSD) was used to compare the four reduced air temperature treatments at $P < 0.05$. Blocks were pooled when the treatment-by-block interaction was not significant or when trends of treatment responses were consistent. A *t*-test was used to compare reduced air temperature treatment means to the commercial control mean.

Results and Discussion

Effects of RZH on rate of flowering. Time to flower decreased with increasing RZH for all cultivars and RILs grown under a reduced air temperature (Table 3.2). For example, TTF of 'Supertunia Bordeaux' was 49, 43, 41, or 39 d for plants grown at a MDT of 15 °C without RZH, or with RZH set points of 21, 24, or 27 °C, respectively. With the exception of 'Potunia Plus Red' and 'Sanguna Patio Red', all plants grown at a MDT of 15 °C with a RZH set point of 27 °C had similar or reduced TTF compared to plants grown at a MDT of 20 °C (commercial control). Time to flower of 'Sun Spun Lavender Star' was reduced by 4.4 d for plants grown on a RZH set point of 27 °C and MDT of 15 °C, compared to the commercial control. On average, flowering of all cultivars and RILs was delayed by 10.7 d when grown at a MDT of 15 °C without RZH, compared to those grown at a MDT of 20 °C (Figure 3.1).

Similar to the findings of the current study, an acceleration in flowering rate of petunia is frequently reported with increasing temperatures (Adams et al., 1998;

Blanchard and Runkle, 2011; Blanchard et al., 2011a; Blanchard et al., 2011b; Kaczperski et al., 1991; Warner, 2010; Vaid and Runkle, 2013). For example, TTF of petunia ‘Snow Cloud’ was 74, 56, or 46 d when grown at a constant air temperature of 15, 20, or 25 °C, respectively (Kaczperski et al., 1991). Vaid and Runkle (2013) used a linear model to describe the rate of petunia flowering in response to increasing MDT from 14 to 26 °C. Blanchard and Runkle (2011) reported a nonlinear response to temperature for petunia ‘Dreams Neon Rose’ and ‘Wave Purple’ with increasing MDT from 5 to 30 °C; plants did not reach T_{opt} within this range, but T_b was calculated to be 2.8 and 5.5 °C for petunia ‘Dreams Neon Rose’ and ‘Wave Purple’, respectively. Petunia can therefore be categorized as cold-tolerant or cold-intermediate, depending on cultivar.

For all cultivars and RILs included in the current study, an inverse relationship was observed between TTF and RZH. Gerovac (2014) also reported a linear decrease in TTF for the seed-propagated petunia ‘Dreams Midnight’ with increased RZH from 18 to 27 °C. For example, TTF decreased by 5, 10, or 12 d for plants grown at a MDT of 16 °C with a RZH set point of 21, 24, or 27 °C, respectively, compared to without RZH (Gerovac, 2014). Similarly, an accelerated rate of flowering with increased root-zone temperature has been reported for poinsettia, chrysanthemum, peace lily (*Spathiphyllum* sp.), African violet, and tomato (Brown and Ormrod, 1980; Janes et al, 1981; Vogelezang, 1988; Vogelezang, 1992; Wulster and Janes, 1984). For example, TTF of chrysanthemum ‘Improved Mefo’ was 84 and 99 d when plants were grown at a day/night temperature of 16/11 °C with RZH of 25 °C or without RZH, respectively (Brown and Ormrod, 1980).

Rate of development is directly influenced by plant temperature, and increased tissue temperature was measured with increased RZH. For example, plant tissue temperature was an average of 15.1, 15.6, 16.3, and 18.1 °C for plants grown at a MDT of 15 °C without RZH, or with a RZH set point of 21, 24, or 27 °C, respectively (Table 3.1). Plant tissue temperature of petunias grown at a reduced air temperature in combination with a RZH of 27 °C was an average of 1.7 °C higher than those in the commercial control. A similar trend of increased tissue temperature with increased RZH has been observed for osteospermum (*Osteospermum ecklonis*), poinsettia, African violet, and begonia (*Begonia ×hiemalis*) (Gerovac, 2014; Olberg and Lopez, unpublished; Vogelezang, 1988; Vogelezang and van Weel, 1989). Vogelezang (1988) also reported that plant tissue temperature was more closely related to root-zone temperature than greenhouse air temperature. Elevated plant tissue temperature could explain why a similar or increased TTF of up to 4 d was observed for most petunia plants grown in a greenhouse where the MDT was reduced by 5 °C when a RZH set point of 27 °C was employed, compared to the commercial control.

Effect of RZH on dry mass accumulation. When harvested at first open flower, SDM of all plants grown at a MDT of 15 °C was higher for plants grown without RZH compared to those grown with RZH. With the exception of the inbred line IA349, all plants grown on RZH had similar SDM regardless of RZH set point. For example, SDM of ‘Potunia Plus Red’ was 5.1, 4.8, and 4.7 g when grown on RZH set points of 21, 24, or 27 °C, respectively (Table 3.2). Conversely, SDM of IA349 decreased by 3 g as RZH set points increased from 21 to 27 °C. Shoot dry mass of ‘Supertunia Bordeaux’, ‘Potunia Plus Purple’, ‘Supertunia Red’, ‘Sun Spun Lavender Star’, and IA349 grown at a MDT of

20 °C was similar to plants grown at a MDT of 15 °C with a RZH set point of 24 or 27 °C. Although, all ‘Sun Spun Burgundy’, ‘Potunia Plus Red’, IA160, and ‘Sanguna Patio Red’ plants had a greater SDM when grown at a reduced air temperature, regardless of RZH, compared to the commercial control.

Similar to other studies, biomass accumulation was reduced when rate of development increased (Brown and Ormrod, 1980; Gerovac, 2014; Shedlosky and White, 1987). This resulted in a lower SDM for plants grown at a reduced air temperature with RZH compared to without RZH. Dry mass accumulation is a direct result of photosynthesis; and is therefore directly related to both net photosynthesis and time for photosynthate production, and thus production time (Heins et al., 2000). Time to flower and SDM were closely related. For example, as TTF of ‘Supertunia Red’ decreased from 53 to 40 d, SDM decreased from 9.2 to 5.2 g, for plants with no RZH to RZH set points of 21 to 27 °C. Since plants grown without RZH took longer to flower, they had a longer production time and therefore more time to produce photosynthates to increase biomass prior to harvest at flowering. Likewise, most plants grown at the higher RZH set points with similar TTF to the commercial control also had similar SDM. For example, TTF and SDM of ‘Potunia Plus Purple’ was 40.2, 40.2 or 42.1 d and 3.1, 3.0, or 2.9 g for plants grown at a MDT of 15 °C with a RZH set point of 24 or 27 °C or at a MDT of 20 °C without RZH, respectively. Gerovac (2014) similarly reported an approximately linear decrease of TTF and SDM with increasing RZH for petunia and snapdragon. Likewise, final dry mass of pansy (*Viola* ×*wittrockiana* ‘Imperial Blue’) and petunia ‘White Cascade’ grown with RZH set points of 16 to 21 °C and a night temperature of 7 °C had

similar dry mass to plants grown without RZH and a night temperature of 16 °C (Shedlosky and White, 1987).

When harvested at first open flower, RDM was an average of 22 to 52% greater for plants grown at a MDT of 15 °C, regardless of RZH, compared to those grown at a MDT of 20 °C (data not shown). A similar decrease in RDM by ≈60% has been reported for snapdragon plants grown at a MDT of 16 °C, regardless of RZH from 18 to 27 °C, compared to those grown at a MDT of 19 °C (Gerovac, 2014). For plants grown without RZH, increased production time due to longer TTF could have caused this increase in RDM. Root-zone heating may also have stimulated root growth, as McMichael and Burke (1998) reported an increase in root growth with increasing RZH to a species-specific T_{opt}. While increasing temperatures of RZH did not show any significant effects on RDM in the current study (data not shown), increased root growth was apparent for some cultivars grown with RZH (Figure 3.1).

Root-to-shoot ratio was higher for ‘Potunia Plus Purple’ and IA349 plants grown at a MDT of 15 °C with a RZH set point of 27 °C, compared to those grown at the ambient MDT of 15 °C without RZH (Table 3.2). All cultivars and RILs had a higher root-to-shoot ratio when grown at a reduced air temperature with a RZH set point of 27 °C, compared to those of the commercial control. Generally, root-to-shoot ratio increased with increasing RZH set points, although this trend was only significant for ‘Potunia Plus Purple’ and IA349. High root-to-shoot ratios with increased RZH are likely due to decreased SDM given hastened flowering and increased RDM due to root-growth promotion with elevated root-zone temperature. Gerovac (2014) similarly reported root growth promotion with RZH, as RDM of petunia ‘Dreams Midnight’ increased by 41 to

68% for plants grown at a MDT of 16 °C with RZH of 21 to 27 °C, compared to those grown at a MDT of 19 °C without RZH. This is another benefit of this production regime, as high root-to-shoot ratio is related to increased crop quality.

Effects of RZH on plant growth and morphology. When measured at first open flower, stem length decreased with increasing RZH for all cultivars and RILs, other than 'Sanguna Patio Red'. On average, stem length was reduced by 0.6 to 8.5 cm for plants grown on a RZH set point of 27 °C compared to those without RZH (Table 3.2). Generally, stem length of plants grown at a MDT of 15 °C was greater than that of plants grown at a MDT of 20 °C, although this difference was reduced when plants were grown with a RZH set point of 27 °C. For example, stem length of 'Supertunia Red' was 17.2, 16.3, 15.2, 13.1, or 13.4 cm for plants grown at a MDT of 15 °C without RZH or on a RZH set points of 21, 24, or 27 °C, or at a MDT of 20 °C, respectively (Table 2). Gerovac (2014) reported a similar trend, as stem length of petunia 'Dreams Midnight' was reduced for plants grown at a MDT of 19 °C compared to a MDT of 16 °C; but stem length was similar for plants grown at a MDT of 19 °C and at a MDT of 16 °C with a RZH set point of 27 °C. Similarly, a decrease in plant height was reported with increasing RZH from 17 to 29 °C for chrysanthemum 'May Shoesmith' plants grown in day/night air temperatures of 24/17 °C (McAvoy and Janes, 1984). Conversely, other crops, such as snapdragon and sweet pepper (*Capsicum annuum*), have been reported to have an increase in stem length with increasing RZH (Abdel-Mawgoud et al., 2005; Hood and Mills, 1994). This dissimilarity in response to RZH is likely due to higher greenhouse air

temperatures in the studies with snapdragon and sweet pepper, compared to in the current study, where air temperatures were reduced.

This trend of decreased growth with increasing RZH was consistent for GI for all cultivars and RILs other than ‘Sun Spun Burgundy’ and ‘Sanguna Patio Red’. Growth index of ‘Sun Spun Burgundy’, ‘Potunia Plus Red’, and ‘Sanguna Patio Red’ was reduced for plants grown at a MDT of 15 °C compared to a MDT of 20 °C. For example, growth index of ‘Potunia Plus Red’ was 18.2, 17.5, 16.8, 16.3, and 16.3 cm for plants grown at a MDT of 15 °C without RZH or with a RZH set point of 21, 24, or 27 °C, or at a MDT of 20 °C. A decreased GI can be considered beneficial to growers as it represents more compact growth, and therefore, potentially, a decreased need for chemical plant-growth regulator (PGR) applications. Similarly, a ≈25% reduction in growth has been reported for poinsettia ‘Annette Hegg Brilliant Diamond’ grown with a RZH set point of 29 °C compared to those grown with a RZH set point of 23 °C (Janes and McAvoy, 1983). This decrease in stem length with increasing RZH is likely again due to a shorter TTF and, consequently, a shorter time period for vegetative growth.

When measured at first open flower, branch number of ‘Supertunia Red’, IA160, and IA349 was higher for plants grown at a MDT of 15 °C without RZH compared to with RZH. Branch number and GI were higher for all plants grown at a MDT of 15 °C compared to a MDT of 20 °C. Overall, plants had decreased growth with increased root-zone and air temperature. Root-zone temperature did not significantly affect node number for most plants, although node number was generally lower for plants grown at a MDT of 15 °C compared to a MDT of 20 °C (data not shown). This could be due to a more rapid

rate of development and, thus, increased number of nodes for plants grown at the higher MDT.

Conclusion

Time to flower decreased with increasing RZH for all plants. All cultivars and RILs, with the exception of ‘Potunia Plus Red’ and ‘Sanguna Patio Red’, developed at a similar rate when grown at a MDT of 15 °C with a RZH set point of 27 °C as when grown at a MDT of 20 °C. Time to flower of ‘Potunia Plus Purple’ and ‘Sun Spun Lavender Star’ plants grown at a MDT of 15 °C with RZH of 24 °C was also similar to those grown at a MDT of 20 °C. Shoot dry mass was closely correlated with TTF, generally resulting in decreased SDM for plants grown at a MDT of 15 °C with RZH, compared to without. Shoot dry mass of most plants grown at a reduced air temperature was similar to the commercial control when RZH of 24 to 27 °C was employed. Stem length of all cultivars and RILs, other than ‘Sanguna Patio Red’, decreased with increasing RZH, resulting in more compact plants.

The reduction in production time that results from decreased TTF can directly relate to increased savings for greenhouse operations. This can take the form of reduced requirement for greenhouse heating as the plants occupy the greenhouse for a shorter period of time, or increased number of production turnovers. Energy-savings of ≈8 to 15% have been previously reported by use of RZH with reduced greenhouse air temperatures (Gerovac, 2014). This is likely due to more direct heating of the plants and air around the canopy without superfluous heating of the entire greenhouse airspace. A reduction in overall plant size, as a function of decreased stem length, GI, branch number,

and SDM, was observed for plants grown at a reduced air temperature with RZH. These effects are considered beneficial to growers as reduced plant size allows for fewer PGR applications, occupies less greenhouse bench space for production, and allows for an increased number of plants per cart for shipping. Given the cultivar-specificity of T_b, careful crop selection for vigorous and cold-tolerant cultivars may be of great importance for production under this heating regime. Overall, results suggest that a high-quality, compact petunia crop can be produced when MDT is reduced to 15 °C, when combined with a RZH set point of 27 °C.

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Table 3.1. Mean daily light integral (DLI) and daily air, canopy, media, and plant tissue temperature for each treatment, each month following transplant. Plants were grown at a mean daily temperature (MDT) of 15 °C and plants were placed on a bench without root-zone heating (No RZH) or with RZH set points of 21, 24, or 27 °C; or plants were grown in a greenhouse without RZH at a MDT of 20 °C as per commercial control (Comm.).

		Mean DLI	Temperature (°C)			
Month	Treatment	($mol \cdot m^{-2} \cdot d^{-1}$)	Air	Canopy	Media	Tissue
Jan.	No RZH	13.0		15.6	16.2	—[z]
	21 °C RZH	11.1	15.9	17.1	20.5	—
	24 °C RZH	11.7		17.2	23.1	—
	27 °C RZH	13.4		17.9	25.2	—
	Comm.	11.0	19.5	18.9	18.6	—
Feb.	No RZH	14.5		14.4	15.3	14.5
	21 °C RZH	13.4	14.9	16.6	21.4	15.2
	24 °C RZH	13.2		17.0	23.3	15.7
	27 °C RZH	14.8		17.1	24.9	16.5
	Comm.	13.0	19.2	18.7	17.8	16.2
Mar.	No RZH	14.8		14.9	15.6	15.7
	21 °C RZH	15.3	15.3	16.2	21.2	15.9
	24 °C RZH	15.1		17.2	23.2	16.8
	27 °C RZH	14.9		17.4	24.2	19.7
	Comm.	14.8	19.2	18.7	17.4	16.5

[z] Fine-wire thermistor inserted on 05 Feb.

Table 3.2. Growth index (GI), branch number, stem length, shoot dry mass (SDM), root-to-shoot (R:S) ratio, and time to flower (TTF) for petunia ‘Sun Spun Lavender Star’, ‘Sun Spun Burgundy’, ‘Supertunia Red’, ‘Supertunia Bordeaux’, ‘Potunia Plus Red’, ‘Potunia Plus Purple’, ‘Sanguna Patio Red’ and recombinant inbred lines, IA160 and IA349. Plants were grown at a mean daily temperature (MDT) of 15 °C and plants were placed on a bench without root-zone heating (No RZH) or with RZH set points of 21, 24, or 27 °C; or plants were grown in a greenhouse without RZH at a MDT of 20 °C as per commercial control (Comm.).

Treatment	GI (cm)	Branch number	Stem length (cm)	SDM (g)	R:S Ratio	TTF (d)
			‘Sun Spun Lavender Star'			
No RZH	16.0 ab[z]	—[y]	11.1 a	†5.0 a	0.05	†46.5 a
21 °C RZH	†14.5 ab	—	†10.1 ab	†3.4 b	†0.06	40.1 bc
24 °C RZH	16.9 a	—	†10.6 a	3.9 ab	†0.05	43.4 ab
27 °C RZH	†13.8 b	—	†9.4 b	†3.3 b	†0.07	†37.6 c
Comm.	16.6	—	11.2	4.0	0.04	42.0
Significance	*		**	**	NS	***
			‘Sun Spun Burgundy'			
No RZH	†15.8	—	10.3 ab	†5.5 a	—	†55.4 a
21 °C RZH	†15.8	—	10.5 a	†4.6 b	—	†52.6 a
24 °C RZH	15.2	—	10.0 ab	†4.8 ab	—	†52.6 a
27 °C RZH	14.9	—	9.7 b	†4.7 b	—	48.1 b
Comm.	14.7	—	10.0	4	—	49.2
Significance	*		*	**		***
			‘Supertunia Red'			
No RZH	—	†10.8 a	†17.2 a	†9.2 a	—	†52.7 a
21 °C RZH	—	†8.8 ab	†16.3 ab	†6.5 b	—	†45.4 b
24 °C RZH	—	†11.1 ab	†15.2 b	†6.9 b	—	†46.1 b
27 °C RZH	—	†10.4 b	13.1 c	5.2 b	—	39.7 c
Comm.	—	9.3	13.4	4.5	—	40.4
Significance		*	***	***		***
			‘Supertunia Bordeaux'			
No RZH	—	†10.2	†18.3 a	†7.5 a	†0.09	†49.4 a
21 °C RZH	—	†9.3	16.0 ab	†5.1 b	†0.16	†42.8 b
24 °C RZH	—	†9.9	15.3 b	4.5 b	†0.24	41.3 bc
27 °C RZH	—	†8.9	†14.5 b	4.3 b	†0.21	38.9 c
Comm.	—	8.0	15.7	4.4	0.12	40.3
Significance		NS	**	***	NS	***

Table 3.2 Cont.

			‘Potunia Plus Red'			
No RZH	†18.1 a	—	†12.6 a	†6.3 a	—	†55.8 a
21 °C RZH	†17.5 ab	—	†11.8 ab	†5.1 b	—	†51.8 b
24 °C RZH	16.8 b	—	11.5 b	†4.8 b	—	†48.7 c
27 °C RZH	16.3 b	—	11.0 b	†4.7 b	—	†47.2 c
Comm.	16.3	—	11.3	3.7	—	44.2
Significance	**		***	***		***
			‘Potunia Plus Purple'			
No RZH	14.6 a	—	8.7 a	†4.0 a	0.08 b	†48.8 a
21 °C RZH	14.2 ab	—	8.2 ab	†3.3 b	0.10 ab	43.3 b
24 °C RZH	†13.4 b	—	†7.6 b	3.1 b	0.12 ab	40.2 b
27 °C RZH	†13.3 b	—	†7.7 b	3.0 b	†0.21 a	40.2 b
Comm.	14.2	—	8.3	2.9	0.08	42.1
Significance	**		***	***	*	***
			‘Sanguna Patio Red'			
No RZH	†16.4	—	9.5	†5.6 a	—	†52.8 a
21 °C RZH	16.0	—	9.1	†4.2 b	—	†47.9 bc
24 °C RZH	16.0	—	8.9	†4.9 ab	—	†49.1 ab
27 °C RZH	15.6	—	9.0	†4.4 b	—	†44.5 c
Comm.	15.2	—	9.0	2.6	—	40.0
Significance	NS		NS	***		***
			IA160			
No RZH	—	†15.0 a	†27.9 a	†19.6 a	—	†66.3 a
21 °C RZH	—	†12.9 b	†25.1 b	†11.3 b	—	†56.9 b
24 °C RZH	—	†12.6 b	24.5 bc	†11.9 b	—	†56.7 b
27 °C RZH	—	11.7 b	22.6 c	†11.1 b	—	51.4 c
Comm.	—	11.6	23.4	10.2	—	50.4
Significance		***	***	***		***
			IA349			
No RZH	—	†19.1 a	†28.2 a	†22.8 a	†0.05 c	†68.2 a
21 °C RZH	—	†16.0 b	†24.6 b	†12.2 b	†0.07 bc	†55.6 b
24 °C RZH	—	15.4 b	21.9 bc	10.4 bc	†0.08 ab	†54 b
27 °C RZH	—	†14.7 b	19.7 c	†9.2 c	†0.10 a	50.5 c
Comm.	—	15.3	20.8	10.4	0.07	51.0
Significance		***	***	***	***	***

† Indicates significant difference from the commercial control based on LSD at $P \leq 0.05$.

NS, *, **, or *** indicates treatments (No RZH, 21, 24, or 27 °C RZH) not significant or significant at $P \leq 0.05$, .01, or .001, respectively.

z Means within column with the same letter are not significantly different based on Fisher’s protected LSD at $P \leq 0.05$.

y Data not collected

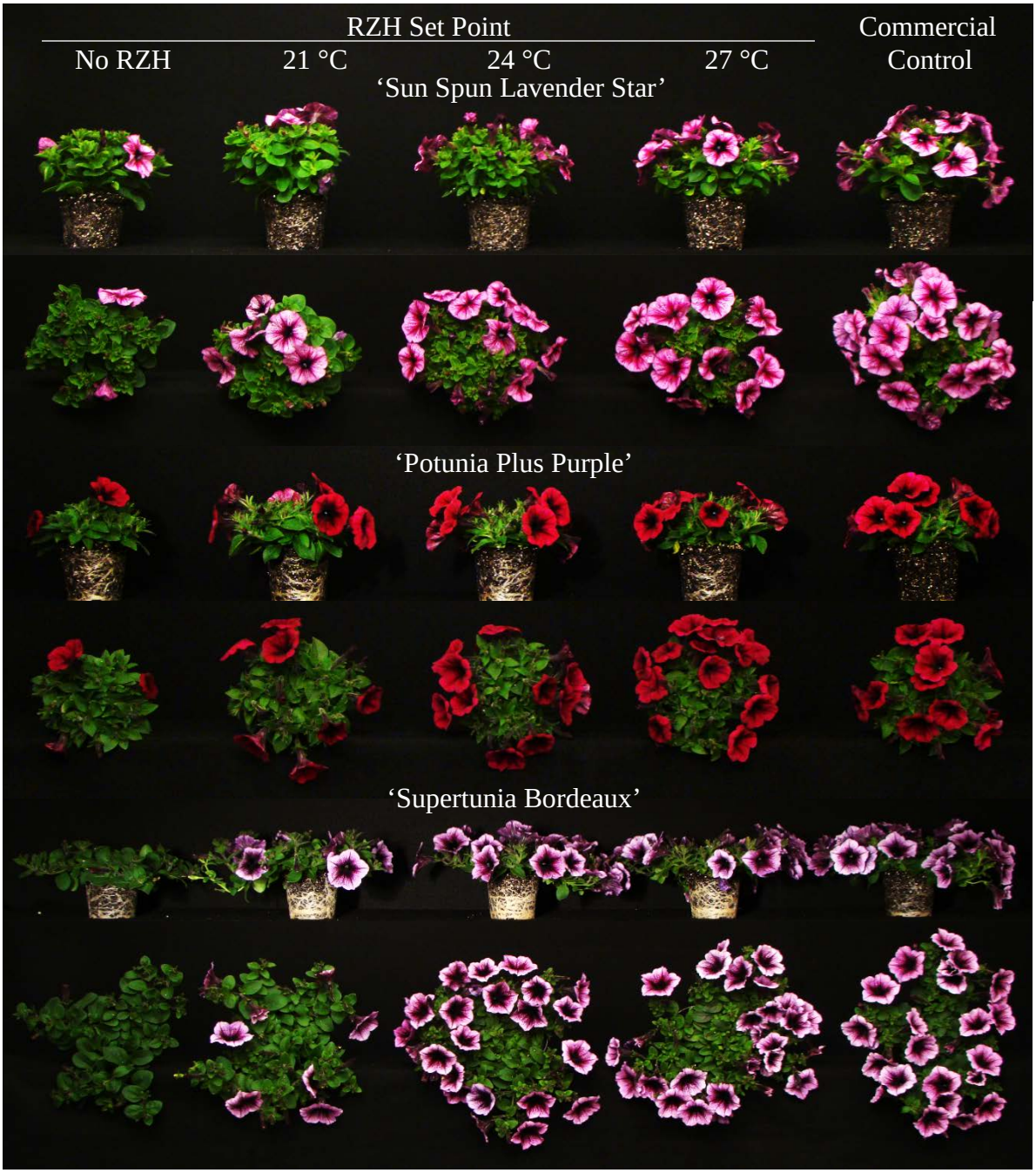

Figure 3.1. Petunia ‘Sun Spun Lavender Star’, ‘Potunia Plus Purple’, and ‘Supertunia Bordeaux’ seven weeks after transplant. Plants were grown at a mean daily temperature (MDT) of 15 °C and plants were placed on a bench without root-zone heating (No RZH) or with RZH set points of 21, 24, or 27 °C; or plants were grown in a greenhouse without RZH at a MDT of 20 °C (Commercial Control).

COMPARISON OF UNHEATED HIGH TUNNEL AND OUTDOOR PRODUCTION OF CONTAINERIZED ANNUAL BEDDING PLANTS IN THE MIDWESTERN UNITED STATES

Abstract

Due to the high cost associated with constructing and operating a greenhouse, some growers have begun using alternative, low-input methods for bedding plant production, such as unheated high tunnel (HT) or outdoor production. Previous research indicates that bedding plant production in unheated HTs may be suitable for cold-tolerant species, but generally delays flowering compared to greenhouse production. To our knowledge, there has been no published research on the effects of outdoor production on bedding plant species. The objectives of this study were, therefore, to 1) compare the growth and development of ten cold-tolerant and intermediate-tolerant annual bedding plant species in an unheated HT or in an unprotected outdoor growing area; 2) evaluate the effect of a one-week acclimation period in the HT prior to outdoor production; and 3) quantify the effectiveness of these production methods for producing high-quality bedding crops. Seedlings of African marigold (*Tagetes erecta* ‘Antigua Orange’), stock (*Matthiola incana* ‘Hot Cakes White’) and primula (*Primula acaulis* ‘Lilac Flame’) and rooted cuttings of calibrachoa (*Calibrachoa* ×*hybrida* ‘Aloha Kona Hot Pink’), regal geranium (*Pelargonium* ×*domesticum* ‘Royal Lavender’), lobelia (*Lobelia erinus* ‘Bella Oceano’), petunia (*Petunia* ×*hybrida* ‘Potunia Plus Red’), phlox (*Phlox maculata* ‘Phloxy Lady

Purple'), osteospermum (*Osteospermum ecklonis* 'Summertime Pink Charme'), and verbena (*Verbena ×hybrida* 'Empress Purple') were transplanted on 13 Apr. 2015 (week 16) into an unheated HT or an outdoor growing area; or into an unheated HT for a one-week acclimation period prior to being moved outdoors. Mean daily air temperature (MDT) was 2.3 °C lower outdoors compared to inside the HT, while mean daily light integral (DLI) increased by 11.7 $mol \cdot m^{-2} \cdot d^{-1}$. All species were delayed when grown outdoors compared to in the HT, and all marigolds grown outdoors died in Apr. when outdoor air temperatures dropped below –4 °C. When plants were acclimated for a one-week period prior to outdoor production, all species, with the exception of regal geranium, were delayed by less than one week compared to those grown in the HT. Stem length of all species grown outdoors was reduced or similar to those in the HT, while biomass accumulation and branch number were not affected or increased for most species. Overall, high-quality bedding plants could be grown outdoors, although development was delayed compared to HT production. Growers must be aware of the risk of crop loss due to extreme temperatures and plan for delays when growing annual bedding plant crops outdoors.

Introduction

Typical annual bedding plant production at northern latitudes occurs from mid-winter to spring in heated greenhouses. Unfortunately, greenhouse heating can account for 10 to 30% of operating costs for those greenhouse operations (Lopez and Runkle, 2014). The high cost and input required for greenhouse production, as well as the high capital cost of building a greenhouse for use only during the short production season, has

therefore given way to the consideration and implementation of alternative, low-cost production methods. One alternative is growing or finishing annual bedding plants in an unheated HT. High tunnels consist of a frame, generally made of pipes or galvanized tubing, covered by a single or double layer of polyethylene (Lamont, 2009). High tunnels typically do not have any type of automated heating, cooling, or ventilation system; and thus are passively solar-heated and cooled via side-wall, end-wall, and/or gable vents (Lamont, 2009). Previous research at Purdue and Cornell Universities has shown that unheated HT production is a plausible method for some cold-tolerant bedding crops, and can even increase crop quality, but development is often delayed (Currey et al., 2014; Gerovac et al., 2015).

Rate of plant development is zero at the species-specific base temperature (T_b), increases linearly to the maximum rate of development at the optimum temperature (T_{opt}), and then decreases rapidly to the maximum temperature (T_{max}), at which point development again ceases. Plants can be categorized by their T_b, such that when $T_b \leq 4$, $4 < T_b < 7$, or $T_b \geq 7$, plants are categorized as cold-tolerant, cold-intermediate, or cold-sensitive, respectively (Blanchard and Runkle, 2011). The lack of active heating in HTs clearly results in a decreased mean daily temperature (MDT) compared to greenhouse production. For example, MDT has been reported to be 6.3 to 7.5 °C and 1.4 to 3.6 °C colder, in Apr. and May, respectively, in a HT compared to in a greenhouse with a MDT set point of 18 to 21 °C in Tippecanoe County, IN (Currey et al., 2014; Gerovac et al., 2015). Consequently, time to flower (TTF) of dianthus (*Dianthus chinensis* ‘Telstar Crimson’), petunia (*Petunia ×hybrida* ‘Wave Pink’), and snapdragon (*Antirrhinum majus* ‘Liberty Classic Yellow’) transplanted on week 13 was delayed by 8, 8, and 26 d when

grown in an unheated HT compared to a heated greenhouse; though, at later planting dates, this delay was minimal or non-existent (Gerovac et al., 2015). Currey et al. (2014) also found that petunia ‘Dreams Midnight’, dianthus ‘Super Parfait Raspberry’, and viola (*Viola* ×*cornuta* ‘Penny Lane Mix’), planted week 14, experienced no delay in development when grown in an unheated HT compared to a heated greenhouse.

As space becomes limiting in the spring, some growers in northern latitudes begin growing outdoors (Crum, 2008; M.W. Olberg, personal observation). However, the morphological and developmental effects of unprotected outdoor bedding plant production are not well documented. Mean daily temperature is often lower in outdoor production than in HTs and therefore further developmental delays could be expected (Wein, 2009). Developmental delays in greenhouse production are extremely undesirable due to the high costs of production per square foot, but crop delays, if planned for, are not as deleterious in low-cost production systems, such as HT or outdoor production. Additionally, the daily light integral (DLI) can be significantly higher in HTs compared to greenhouses and would be even higher outdoors (Currey et al., 2014; Gerovac et al., 2015). High DLIs have been reported to hasten flowering and improve overall crop quality, in terms of increased biomass accumulation, increased branching, more compact growth, and increased number of visible buds (Adams et al. 1998; Blanchard et al., 2011a; Blanchard et al., 2011b; Faust et al., 2005; Heins et al., 2000; Kaczperski et al., 1991; Oh et al., 2010). The production of more compact plants due to high DLI and increased air movement in outdoor production could also limit the need for chemical plant-growth regulator (PGR) applications (Crum, 2008; Faust et al., 2005; Latimer, 1998; Liu and Heins, 2002; Moccaldi and Runkle, 2007). These benefits could

consequently make HT or outdoor production systems suitable for cold-tolerant and cold-intermediate bedding plant crops, although the risks of crop loss due to weather extremes must also be considered. High tunnel or outdoor production may also benefit the ultimate consumer, as plants become acclimated to outdoor conditions during production, prior to transplant into the landscape.

While there is published information on the growth and development of various bedding plant species in unheated HTs, to our knowledge, there is no published information on the effects of unprotected outdoor production on cold-tolerant and intermediate bedding plants, especially in northern latitudes. Therefore, the objectives of this study were to 1) compare the growth and development of ten annual bedding crop species grown in an unheated HT or outdoors; 2) evaluate the effect of a one-week acclimation period in the HT prior to outdoor production; and 3) quantify the effectiveness of these production methods for producing high-quality bedding crops. This information could be very valuable for growers to determine what crops can be produced outdoors and what they can expect in terms of crop timing, morphology, and freezing injury; and for exemplifying any effects of an acclimation period prior to outdoor production.

Materials and Methods

Plant material and culture. Between 19 Mar. and 25 Mar. 2015 (weeks 12 to 13), seedlings of African marigold (*Tagetes erecta* ‘Antigua Orange’), stock (*Matthiola incana* ‘Hot Cakes White’) and primula (*Primula acaulis* ‘Lilac Flame’) in 288-cell (6-mL individual cell vol.) plug trays were received at Purdue University, West Lafayette,

IN (Purdue; lat. 40° N). On week 15 (08 Apr. 2015), rooted cuttings of calibrachoa (*Calibrachoa ×hybrida* ‘Aloha Kona Hot Pink’), regal geranium (*Pelargonium ×domesticum* ‘Royal Lavender’), lobelia (*Lobelia erinus* ‘Bella Oceano’), petunia ‘Potunia Plus Red’, phlox (*Phlox maculata* ‘Phloxy Lady Purple’), osteospermum (*Osteospermum ecklonis* ‘Summertime Pink Charme’), and verbena (*Verbena ×hybrida* ‘Empress Purple’) in 51-cell (27.2-mL individual cell vol.) liners were received at Purdue. Plants were held until 13 Apr. 2015 (week 16) in a glass-glazed greenhouse at a MDT (mean ± SD) of 15.7 ± 3.1 °C and a mean DLI (mean ± SD) of 11.8 ± 3.5 $mol \cdot m^{-2} \cdot d^{-1}$. All plants were irrigated as necessary with clear water, supplemented with 93% sulfuric acid (Brenntag, Reading, PA) at 0.08 $mL \cdot L^{-1}$ to reduce alkalinity to 100 $mg \cdot L^{-1}$ and maintain pH within the range of 5.8 to 6.2. Prior to transplant, plants were fertigated twice weekly with clear, acidified water supplemented with two water-soluble fertilizers (3:1 mixture of 15N–2.2P–12.5K and 21N–2.2P–16.6K, respectively; Everris NA, Inc., Dublin, OH) to provide (in $mg \cdot L^{-1}$): 200 N, 26 P, 163 K, 50 Ca, 20 Mg, 1.0 Fe, 0.5 Mn and Zn, 0.24 Cu and B, and 0.1 Mo.

All plants were transplanted on 13 Apr. 2015 (week 16) into 11.4 cm (600 mL) containers filled with soilless substrate consisting of (by vol.) 65% peat, 20% perlite, and 15% vermiculite (Fafard 2 Mix; SunGro Horticulture, Agawam, MA). Thirty-two randomly selected plants of each species were moved into an east-west oriented HT and 16 randomly selected plants of each species were moved to an unprotected outdoor growing area, adjacent to the HT. All containerized plants were placed into shuttle trays on top of a single layer of commercial grade landscape fabric outdoors and in the HT.

After a one-week acclimation period in the HT, 16 plants of each species were moved from the HT to the outdoor growing area.

All plants were overhead hand-irrigated as necessary with clear water, supplemented with 93% sulfuric acid (Mallinckrodt Chemicals, St. Louis, MO), to reduce alkalinity to ≈100 $mg \cdot L^{-1}$ calcium carbonate ($CaCO_3$), and water-soluble fertilizer (Peters Excel 21-5-20; Everris NA, Inc.) to provide (in $mg \cdot L^{-1}$): 200 N, 26 P, 163 K, 1.0 Fe, 0.5 Mn and Zn, 0.24 Cu and B, and 0.1 Mo. After rain events, plants in the HT were irrigated with clear, acidified water to imitate similar saturation and leaching to outdoors.

High tunnel and outdoor growing area environments. High tunnel and outdoor environments were located at the Meigs Farm, Throckmorton Purdue Agriculture Center, Tippecanoe Co., IN (lat. 40.29º N, long. 86.88º W). A single layer of clear greenhouse-grade, 6-mil polyethylene covered the 7.3 × 14.6 m HT structure (Altas Snow Arch; Atlas Manufacturing, Inc., Alapaha, GA). Ventilation was automated using a motorized crank system (E-Z Roll-Up Motorized Crank System; Atlas Manufacturing, Inc.) with an electronic controller (Atlas 24-volt Natural Ventilation Controller; Atlas Manufacturing, Inc.) powered by two electric solar panels to roll up the side-walls. Side-walls were set to open to 1 m height when air temperature inside the HT reached 29 °C and to close when inside air temperature dropped below 17 °C. Gable vents were set to open at 25 °C using a heat-activated louver opener (Atlas Manufacturing, Inc.). On nights when outdoor forecast temperature lows were predicted to be <3 °C, rowcover (Agribon+AG-19; Agribon, San Luis Potosi, Mexico) was pulled over plants outdoors, and when predicted to be <1 °C, rowcover was pulled over all plants, in the HT and outdoors.

Environmental data collection. Air temperature at plant canopy level was measured every 20 s using an enclosed thermocouple, and averages were calculated and recorded every 15 min by a data logger (Model 2475 Plant Growth Station; Spectrum Technologies, Plainfield, IL). Media temperatures and photosynthetic photon flux (*PPF*) were measured every 30 s using resistance-based temperature sensors (External Temperature Sensor; Spectrum Technologies) inserted horizontally in the media and quantum sensors (Model SQ-212; Apogee Instruments Inc., Logan, UT) placed at plant height, respectively. Mean media temperature and DLI were recorded every 15 min by a data logger (WatchDog 2800 Weather Station; Spectrum Technologies). Mean DLI and mean, minimum, and maximum media and air temperatures were calculated for each month for each growing environment (Table 4.1).

Data collection and calculations. Plants were monitored daily and date of first open flower was recorded for marigold, primula, regal geranium, osteospermum, and verbena when the first flower was fully reflexed. Date marketable was recorded for calibrachoa, regal geranium, lobelia, phlox, and petunia, due to premature flowering, when plants had at least one open flower and filled out the container, completely covering all exposed media. Time to flower and time to marketable (TTM) were calculated as the number of days from transplant (13 Apr.) to date of flowering or marketability, respectively. Stem length was measured for all species from the base of the plant to the apical meristem. Plant width and perpendicular width were also measured for all species; and growth index [GI; (stem length + plant width + plant perpendicular width)/ 3] was calculated. Number of nodes below the first open flower was determined for marigold, primula, petunia, osteospermum, and verbena. Branch number was also

recorded for all species, with the exception of stock and primula. Inflorescence size was measured for stock from the lower- to upper-most floret. Plant growth parameters, including stem length, plant width, node number, branch number, and/or inflorescence size, were measured at flowering for marigold, primula, osteospermum, and verbena, at marketable for calibrachoa, regal geranium, lobelia, phlox, and petunia, and 38 d after transplant for stock. Shoots of six plants per species per replication were excised at the growing media surface and dried in an oven at 70 °C for at least 4 d. After drying, shoots were weighed to determine shoot dry mass (SDM).

Experimental design and statistical analysis. The experiment was a complete randomized block design, with two replications and blocked by treatment (growing environment). Each replication had eight experimental units (single plant in a container) per species, which were randomized within each block. Replications were pooled based on consistent trends of treatment response. Means of treatments were compared by *t*-test using SAS (SAS version 9.4; SAS Institute, Cary, NC) PROC TTEST at $P \leq 0.05$.

Results and Discussion

Environmental conditions of high tunnel and outdoor production. As expected, mean air and media temperatures were consistently lower outdoors, compared to in the HT (Table 4.1). Additionally, minimum recorded temperature was 2.4 and –4.2 °C in the HT and outdoors, respectively. Despite the use of rowcover fabric, it is apparent that the HT was able to buffer some of the extreme night temperatures, especially early in production. Outdoor air temperatures fell below freezing on five nights in Apr., while HT temperatures remained above 2 °C. Ventilation may have been limiting later in HT

production, though, as a temperature extreme of 53.7 °C occurred in June in the HT, while the maximum outdoor air temperature was only 33.3 °C. This could be due to the width of the HT used, as it has been reported that passive HT ventilation may not be adequate for HTs wider than 6 m when outdoors air temperatures exceed 30 °C (Wells and Loy, 1993). This also may have been caused by technical errors with the automatic motorized crank system and controls. The extreme temperature was likely temporary as no heat stress was visually observed. Media temperatures were consistently higher than air temperatures and displayed less fluctuation. High media temperatures were likely due to the black containers, shuttle trays, and landscape fabric below all plants. The landscape fabric in the HT and outdoor plot was often warm or even hot to touch, hence heating the root-zone via conduction. Mean daily temperature fluctuated more outdoors than in the HT, apparent by the consistently larger standard deviations (Table 4.1). Plants that were given a one-week acclimation period in the HT were exposed to a higher MDT in Apr.

Mean DLI was consistently reduced by ≈27% in the HT compared to outdoors. Single-layer polyethylene allows for 87% transmission of photosynthetically active radiation (PAR; 400 to 700 nm) (Bartok et al., 2001); thus, reduced transmission through the plastic covering and shading from the HT structure likely caused the observed decrease in DLI. Daily light integral outdoors was also reduced when rowcover was used to cover the crop in the late afternoon and morning. However, the rowcover provided ≈85% light transmittance, so effects on DLI were likely minor. Although light levels were reduced in the HT compared to outdoors, HTs still allow for significantly increased DLI compared to greenhouses. For example, DLI in the HT has been reported as 9.3 to

22.3 $mol \cdot m^{-2} \cdot d^{-1}$ higher than in the greenhouse in Apr. through June (Currey et al., 2014; Gerovac et al., 2015).

Effects of high tunnel versus outdoor production on rate of plant development. After a few nights below freezing in Apr., all marigold plants growing outdoors had symptoms of freezing injury and died. Marigold was therefore excluded from further analysis. All species developed more rapidly in the HT than outdoors (Table 4.2). Plant development is directly related to MDT (Blanchard and Runkle, 2011; Vaid and Runkle, 2013). Therefore, the overall reduced air and media temperatures, by 2.3 and 1.5 °C, respectively, in outdoor production, likely caused the delay in flowering and marketability. When grown outdoors compared to in the HT, primula, calibrachoa, and verbena were delayed by only 4, 6, and 7 d, respectively; lobelia, phlox, and petunia experienced intermediate delays of 9, 9, and 11 d, respectively; and regal geranium was delayed by 26 d. Similarly, Currey et al. (2014) reported delays of 3 to 13 d for cold-tolerant and cold-intermediate annual bedding plants grown in a HT compared to in a greenhouse, with a decrease in MDT of 3.6 to 7.5 °C. Likewise, delays of 2 to 17 d were reported for dianthus, petunia, and snapdragon transplanted into a HT on week 14, compared to into a greenhouse, with a decrease in MDT of 1.4 to 6.6 °C (Gerovac et al., 2015). Given the delay in development of HT production compared to greenhouse, additional delays should be expected when comparing outdoor production to greenhouse production.

Effects of high tunnel versus outdoor production on plant growth and morphology. Growth is a function of net photosynthesis, which is affected by both temperature and DLI (van Iersel, 2003). While mean outdoor temperatures were lower

than in the HT, light levels were higher; thus increasing the photothermal ratio, or the ratio of radiant energy to thermal energy (mol·m^{-2} per degree-day). Photothermal ratio has been proposed to balance the ratio of plant growth to plant development and increased photothermal ratio has been reported to increase overall crop quality (Blanchard et al., 2011a; Liu and Heins, 2002). For example, increased photothermal ratio resulted in increased biomass accumulation, stem diameter, and inflorescence diameter and decreased plant height of poinsettia (*Euphorbia pulcherrima* 'Freedom'), all conferring increased plant quality (Liu and Heins, 2002). Photothermal ratio has also been reported to be positively correlated with flower bud number and negatively correlated with plant height of petunia (Blanchard et al., 2011a). As expected, with increased photothermal ratio in outdoor production, reduced stem length and GI was observed for lobelia, osteospermum, stock, and verbena grown outdoors, compared to in the HT (Table 4.2). Growing environment had no effect on stem length for all other species; although petunia had an increased GI when grown outdoors compared to in the HT. Reduced stem length of plants grown outdoors is likely also a result of thigmomorphogenesis, such as by wind and precipitation (Downs and Krizek, 1997; Latimer, 1998; Mitchell, 1996). Mechanical stress has been reported to reduce plant height by 20 to 50% (Latimer, 1998). These reductions are similar to results of PGR application, and thus could minimize the need for chemical height control in outdoor production (Latimer, 1998).

Shoot dry mass of calibrachoa, regal geranium, petunia, and phlox was higher for plants grown outdoors compared to in the HT, which could be a result of increased photothermal ratio, increased DLI, or increased time to accumulate biomass (Faust et al.,

2005; Liu and Heins, 2002; Moccaldi and Runkle, 2007). Faust et al. (2005) reported increasing plant dry mass with increasing DLI from 5 to 43 $mol \cdot m^{-2} \cdot d^{-1}$ for eight bedding plant species. Similar studies have also found increased SDM at flowering with decreased MDT, due to increased production time, which could describe the same trend observed in the present study, as temperatures were consistently lower outdoors than in the HT (Moccaldi and Runkle, 2007; Vaid et al, 2014). Net photosynthesis has been found to be maximal at 14 to 15 °C for multiple annual plant species (van Iersel, 2003). Biomass accumulation is a result of net photosynthesis and duration of photosynthate accumulation. Low air temperature and high DLI, resulting in an increased photothermal ratio, as well as increased TTF and TTM, likely caused the observed increase in SDM outdoors. In contrast, osteospermum and stock had decreased SDM when grown outdoors compared to in the HT. Low outdoor temperatures may have limited photosynthetic ability or damaged the cellular photosynthetic apparatus for these crops. When grown outdoors, osteospermum and stock exhibited a decrease in overall size, in terms of stem length, GI, and SDM. Node number of osteospermum and inflorescence size of stock were also reduced for plants grown outside compared to those in the HT (data not shown). Node number was similar for all other species grown outdoors or in the HT. Similarly, previous studies have reported that DLI and temperature did not consistently affect node number (Moccadli and Runkle, 2007; Vaid and Runkle, 2013). Branch number at flowering increased for calibrachoa and regal geranium grown outdoors compared to in the HT. All other species had similar branch number regardless of growing environment. Branching is generally positively correlated with DLI and inversely related to MDT (Faust et al., 2005; Kaczperski et al., 1991; Vaid et al., 2014).

This likely balanced the effects of HT and outdoor production, as MDT was lower, but DLI was higher outdoors compared to in the HT.

Effects of an acclimation period prior to outdoor production. When plants were given a one-week acclimation period in the HT prior to outdoor production, all species, with the exception of regal geranium, were delayed by one week or less (2 to 7 d) compared to when grown in the HT. This may highlight the importance of an acclimation period early in production to reduce developmental delay for some crops. Gerovac et al. (2015) reported that an acclimation period of 1 to 2 weeks in the greenhouse at 21 °C prior to transplant into the HT reduced TTF for some crops, such as petunia and snapdragon, but had no effect on TTF of dianthus. An acclimation period in the HT prior to outdoor production significantly hastened development in calibrachoa, lobelia, petunia, and phlox, but did not cause any significant effect on development in other species. The one-week acclimation period had little to no effect on growth and morphology of all species.

Conclusion

Overall, plant development was delayed for all species grown outdoors compared to in the HT. These delays varied by species from only 4 d (primula) to 26 d (regal geranium). All species, other than regal geranium, acclimated in the HT for one week prior to being grown outdoors, were delayed by less than one week compared to those grown entirely in the HT. Later planting dates or implementation of an acclimation period could potentially prevent or reduce developmental delays, as early spring cold temperatures could be avoided or reduced (Gerovac et al., 2015).

Stem length at flowering was reduced or similar for all plants grown outdoors compared to in the HT, while SDM and branch number of most species grown outdoors was greater than or equal to those grown in the HT. Given that compact and well-branched plants with high SDM are considered high-quality annual bedding plants, most crops produced outdoors were of equal or greater quality to those in the HT (Vaid et al., 2014). This increased quality is likely a result of the increased photothermal ratio, DLI, and air movement observed outdoors compared to inside the HT (Blanchard et al., 2011a; Downs and Krizek, 1997; Faust et al., 2005; Liu and Heins, 2002). Outdoor production may therefore be suitable for production of some cold-tolerant and cold-intermediate bedding crops and could reduce the need for PGR applications; but growers must plan for some delay and be aware of the risk of crop loss due to extreme weather in early spring.

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Table 4.1. Mean daily light integral (DLI) and mean, minimum (min), and maximum (max) media and air temperature for each growing environment (GE), each month following transplant. Plants were transplanted on 13 Apr. 2015 and then grown in a high tunnel (HT), in a HT for a one-week acclimation period then outdoors (HT/O), or outdoors (O).

		DLI[z]	Media Temperature (°C)			Air Temperature (°C)		
Month	GE	($mol \cdot m^{-2} \cdot d^{-1}$)	Mean[z]	Min	Max	Mean[z]	Min	Max
Apr.	HT	27.7 ± 11.7	16.4 ± 3.9	4.5	37.1	13.7 ± 4.5	2.4	32.6
	HT/O	35.9 ± 17.4	13.8 ± 7.4	1.8	37.1	11.8 ± 7.0	-4.2	32.6
	O	39.2 ± 17.0	12.2 ± 4.6	1.8	32.5	11.0 ± 5.3	-4.2	26.6
May	HT	30.7 ± 9.1	22.8 ± 5.3	7.9	41.9	20.7 ± 7.1	2.8	37.8
	O	43.4 ± 13.2	20.3 ± 6.6	3.1	44.8	19.0 ± 8.2	0.2	32.0
June	HT	36.1 ± 7.3	26.1 ± 5.0	13.8	49.3	22.5 ± 6.4	9.6	53.7
	O	46.9 ± 13.0	24.0 ± 6.2	8.8	47.6	20.7 ± 11.0	6.7	33.3

[z] Mean ± SD

Table 4.2. Mean stem length, growth index (GI), node number, branch number, shoot dry mass (SDM), time to flower (TTF), and time to marketable (TTM) of ten annual bedding plant crops transplanted on 13 Apr. 2015 and then grown in a high tunnel (HT), in a HT for a one-week acclimation period then outdoors (HT/O), or outdoors (O).

Treatment	Stem length (cm)	GI (cm)	Node number	Branch number	SDM (g)	TTF (d)	TTM (d)
Calibrachoa							
HT	7.6 a[z]	14.4 a	—[y]	14.9 b	2.4 b	—	28.5 c
HT/O	7.7 a	14.2 a	—	21.0 a	2.8 a	—	32.3 b
O	7.8 a	14.5 a	—	21.5 a	2.9 a	—	34.0 a
Regal Geranium							
HT	12.4 a	11.9 a	—	8.6 b	3.2 b	30.6 b	35.4 b
HT/O	11.3 a	12.2 a	—	10.1 a	4.7 a	48.3 a	49.3 a
O	11.9 a	13.5 a	—	9.8 a	5.9 a	56.8 a	56.8 a
Lobelia							
HT	10.0 a	14.9 a	—	12.4 a	2.0 a	—	25.6 c
HT/O	8.5 b	15.0 a	—	7.4 b	2.3 a	—	31.0 b
O	9.2 b	15.2 a	—	13.1 a	2.5 a	—	34.4 a
Osteospermum							
HT	17.5 a	19.0 a	20.9 a	8.3 a	9.1 a	49.4 b	—
HT/O	12.2 b	14.6 b	17.6 b	8.0 a	7.0 b	53.6 a	—
O	12.5 b	14.5 b	18.0 b	7.3 a	6.6 b	53.5 a	—
Petunia							
HT	13.0 a	16.2 b	12.8 a	12.8 a	3.1 b	—	24.3 c
HT/O	12.2 a	16.9 b	12.6 a	12.6 a	4.9 a	—	30.9 b
O	13.0 a	18.8 a	14.3 a	14.3 a	4.4 a	—	35.6 a
Phlox							
HT	8.8 a	13.9 a	—	14.5 a	2.2 b	—	31.4 c
HT/O	9.0 a	12.8 ab	—	16.1 a	2.7 a	—	36.3 b
O	8.5 a	12.2 b	—	17.3 a	2.7 a	—	40.3 a
Primula							
HT	5.8 a	10.4 a	13.7 a	—	1.8 a	45.1 a	—
HT/O	6.0 a	10.5 a	15.8 a	—	1.9 a	47.5 a	—
O	6.1 a	10.5 a	12.4 a	—	1.6 a	48.6 a	—
Stock							
HT	14.8 b	16.3 a	6.0 a	—	3.8 a	—	—
HT/O	15.7 ab	16.2 a	7.5 a	—	3.8 a	—	—
O	12.4 a	13.8 b	7.7 a	—	3.0 b	—	—

Table 4.2 Cont.

				Verbena			
HT	12.5 a	26.7 a	4.6 a	5.3 a	5.4 a	33.0 b	—
HT/O	10.2 b	21.5 b	4.8 a	5.1 a	5.2 a	37.9 a	—
O	10.2 b	21.3 b	4.9 a	4.6 a	5.0 a	39.8 a	—
				Marigold[x]			
HT	16.8	19.3	7.6	—	7.3	34.1	—
HT/O	—	—	—	—	—	—	—
O	—	—	—	—	—	—	—

[z] Means with the same letter within a column per species are not different based on a *t*-test at $P \leq 0.05$.

[y] Data not collected

[x] All marigolds grown outdoors died due to low temperature